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Regionalization as a Tool for Managing Environmental Resources

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REGIONALIZATION AS A TOOL FOR MANAGING ENVIRONMENTAL RESOURCES

by

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ABSTRACT

Many environmental resource managers have recognized the need for regional management frameworks. The natural and human-imposed characteristics governing environmental resources vary throughout the country, likewise altering the issues of concern. There are, however, areas (regions), definable at any resolution, within which these characteristics and concerns are relatively homogeneous. By mapping these areas, a regional management framework can be developed. The purpose of this report is to explain the concept and nature of regions and the utility of a regional framework for resource management. In this report we (1) discuss the nature of regions and boundaries, (2) review some of the more popular regional frameworks, pointing out their attributes and limitations, (3) explain our synoptic approach for defining regions, and provide examples where the approach was applied to assess surface water quality, (4) describe the process for selecting regionally representative reference sites, (5) demonstrate methods of analyzing data from such sites for extrapolating results to larger areas, (6) examine ways that an ecoregional framework was applied to establish water resource criteria in accord with regional capacities for buffering environmental changes, and (7) propose other areas of management that might benefit from regional assessment techniques.

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TERMINOLOGY

This list provides general working definitions of some of the terms used in this report.

Aquatic life use - A designated water body use that specifies the protection and propagation of fish, shellfish, and wildlife (40 CFR Part 13).

Attainable quality - A concept based on the expected condition of a resource as sustained by natural environmental characteristics unaltered by human perturbation; usually, we can only approximate such circumstances by examining sites having minimal interference from human influence.

Biological criteria (Biocriteria) - Numerical or narrative expressions of the biological characteristics of ambient aquatic communities, often structural measures (e.g., species composition, organism abundance, and diversity).

Criteria - Constituent concentrations, levels, or narrative statements representing a quality of water presumed to support a particular use (40 CFR Parts 35, 120, 131).

Designated uses - Specified goals for water bodies. These include uses for public water supplies, protection and propagation of fish, shellfish, and wildlife, recreation in and on the water, and agricultural, industrial, and other purposes (40 CFR 35, 120, 131).

Detrended correspondence analysis - An ordination technique often used to show the relationships among sites based on biological data.

Dimictic lake - A lake that undergoes two turnover events annually (usually in spring and fall), resulting in either partial or complete mixing of different layers of the water.

Discriminant analysis - Statistical analysis for examining the influence of different environmental factors on patterns observed in ordinations.

Drainage area - See Watershed.

Ecological integrity - The ability of an ecosystem to sustain a balanced biotic community. The natural environmental characteristics of the ecosystem determine the nature of its biotic community; alterations of physical, chemical, or biological processes within the ecosystem can have a major impact on biota, and thus on ecological integrity.

Ecoregion - An area (region) of relative homogeneity in ecological systems.

Ephemeral stream - A stream that flows only in response to major precipitation or meltwater events.

Hypolimnion - The deep water region below the well-mixed layer in a lake.

Index of Biotic Integrity (IBI) - A measure of stream ecological health based on fish species richness, composition, abundance, condition, and trophic composition.

Index of Well Being (IWB) - A measure of fish community health based on abundance and weight, and the diversity of both.

Intermittent stream - A stream that flows (generally) part of every year.

Invertebrate Community Index (ICI) - A measure of stream health based on several metrics of the macroinvertebrate community. Uses ecological principles similar to those of the IBI.

Kjeldahl nitrogen - The sum of the organic and ammonia nitrogen components in water samples. High concentration of nitrogen in surface waters is not necessarily damaging to aquatic biota, but may indicate that other, more deleterious compounds are also present in the systems.

Lake total phosphorus - Total dissolved and particulate phosphorus in lake water samples. Phosphorus is essential to the growth of organisms, but high concentrations of phosphorus may stimulate nuisance quantities of aquatic vegetation.

Least impacted site - A site at which conditions represent minimal interference from human influence.

Local relief - The elevational change in topography within a 10 km^2 area.

Minimally impacted site - See Least impacted site.

Multivariate analysis - Any of a set of statistical techniques for examining many environmental factors simultaneously; we use primarily ordination analyses.

Nonpoint source pollution - Pollution from diffuse sources of land runoff into water bodies, such as from areas of fertilizer and pesticide application or soil erosion.

Ordination - A set of statistical techniques that arrange sites or environmental variables (chemical, physical, or biological) in relation to one or more coordinate axes such that their positions relative to the axes and to each other provide maximum information about their ecological similarities.

Perennial stream - A stream that flows year-round.

Physiography - Pertains to the genesis, structure, and evolution of landforms.

Point source pollution - Pollution originating from a discrete source, such as outflow from a pipe or a concentrated animal feeding operation.

Polymictic lake - A lake in which turnover events occur at frequent intervals during the year, often daily.

Principal components analysis - An ordination technique often based on chemical or physical data and used to show the relationships among sites.

Quality assurance/Quality control (QA/QC) - A quality assurance program sets data quality objectives during the design phase of a project, focusing on the levels of accuracy and precision needed. Quality control procedures are performed throughout data collection and analysis to meet the objectives specified by the quality assurance plan.

Reference sites - Areas (watersheds, stream reaches, lakes, etc.) whose environmental characteristics are representative of other areas and whose measured data values are inferred to indicate those of other areas.

Region - An area of relative homogeneity for a particular set of characteristics.

Resolution - The level of detail represented on a map or in a data set.

Scale - The ratio of the distance between two points on a map to the distance between the same points on the earth. The smaller the ratio (fraction), the smaller the map scale.

Spatial distribution - The areal arrangement of attributes (e.g., environmental characteristics, data values, species, land use types, etc.).

Synoptic approach - A technique for simultaneously evaluating the associations among spatial distributions of different environmental characteristics as indicated by numeric or mapped data.

Thematic specificity - The objective of a thematic map is to focus on the structure of a particular distribution. The degree of uniqueness of that distribution represents its specificity.

Total organic carbon - The amount of organically bound carbon in a water sample. High levels may indicate organic enrichment that could lead to oxygen depletion as the organic carbon is consumed.

Trophic state - The intensity of primary productivity in a water body, often estimated by the nutrient (nitrogen and phosphorus) enrichment to the water body.

Univariate analysis - Any statistical technique for examining (environmental) factors singly.

Water quality standards - Standards defining water quality goals of a water body, or a portion thereof, by designating the use or uses to be made of the water and by setting criteria necessary to protect those uses (40 CFR Parts 35, 120, 131).

Water Quality Standards Regulation - The Regulation governing the development, review, revision, and approval of water quality standards under Section 303 of the Water Quality Act.

Watershed - An area of land draining to a specific point on a stream or to a lake or wetland.

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EXECUTIVE SUMMARY
REGIONALIZATION AS A TOOL FOR MANAGING ENVIRONMENTAL RESOURCES

APPLICATIONS OF A REGIONAL APPROACH

All of us are familiar with different kinds of regions. We recognize political regions, perceiving the world as a hierarchical set of units: continents comprising countries comprising states, counties, cities, districts, and neighborhoods. We recognize cultural regions, identifying people by their appearance, mannerisms, and speech patterns. We also recognize environmental regions, examining world biomes, the ecosystems within them, and the smaller habitat types within the ecosystems. In a more formal sense, a region is associated with a specific location that covers some extent of area and contains a certain degree of homogeneity with respect to the characteristics used to define it. Wiken (1986) explains that, "Regionalization is a method of reducing or eliminating details which do not, on the average, hold true over large areas."

The purpose of this report is to explain the concept and nature of regions and the utility of a regional framework for resource management. Discussions are divided into four main sections. The first covers some major components of regional representation, the utility of regional frameworks for selecting reference sites, principal factors contributing to the delineation process, and examples of popular regional frameworks. The second introduces the approach used by the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon, to develop environmental regional frameworks for research and management. The third presents methods for evaluating correspondence between regions and patterns in other environmental data and incorporates discussion on data sources, type, quality, and quantity, regional sampling options, and methods of regional data analysis. The fourth relates the applicability of regional analysis for addressing state and national management mandates related to water quality standards and water body monitoring, assessment, and reporting, and briefly describes additional fields of potential application of a regional approach.

Our major stimulus for developing an ecoregional framework has come from a need to assess existing and attainable surface water quality. Traditionally, the emphasis has been to set goals based on chemical or toxicological criteria, and to control point source pollution to protect designated uses of water bodies by achieving those goals. Recently, increased attention has been directed toward the quality of specific receiving waters and ambient biological criteria. An essential component of addressing these issues is a management framework that can be used to:

- Compare ecological similarities and differences
- Establish meaningful and reasonable physical, chemical, and biological goals and criteria
- Select representative sample sites needed for defensible data
- Extrapolate results to larger areas

- Identify areas that should receive additional resource protection
- Predict the effects of management on resource quality

Two states, Arkansas and Ohio, have adopted a regional framework for setting chemical and biological criteria to supplement the traditional methods of water quality management. A third state, Minnesota, has used a regional framework to organize, present, and interpret water quality information.

a. **Arkansas** found that in some ecoregions, national criteria could not be achieved even in minimally impacted streams, whereas in other ecoregions, the criteria were not stringent enough. As a result, the state developed regionally specific aquatic life use designations and water quality criteria (e.g., for dissolved oxygen, temperature, and turbidity).

b. **Ohio** established ecoregional numerical criteria for biota in streams. The biological criteria were based on the composition and relative abundance of fish and macroinvertebrate assemblages sampled at least impacted regional reference sites. These data were used to establish regionally attainable criteria for the Index of Biotic Integrity, the Index of Well-Being, and the Invertebrate Community Index, developed to measure the health of fish and macroinvertebrate communities. A comparison of ambient chemical criteria versus biological criteria to indicate stream impairment showed agreement in 46% of the cases; biological criteria indicated greater impairment than did chemical criteria in 41% of the cases; chemical criteria indicated greater impairment than did biological criteria in 12% of the cases. Thus, streams meeting chemical criteria cannot necessarily be assumed to be meeting biological criteria, and vice versa. It is necessary to measure both sets of criteria in order to make a complete statement about stream conditions.

c. **Minnesota** developed detailed descriptions of the land and waterbody characteristics of each of its seven ecoregions. For example, in the Northern Lakes and Forests Ecoregion, lakes are generally small, deep, and stratified, whereas in the agricultural Northern Glaciated Plains Ecoregion, lakes are large, shallow, and unstratified. To evaluate these differences, existing lake water quality was analyzed within an ecoregion framework. The framework accounted for a substantial part of the spatial variation in lake water quality, particularly for measures of lake eutrophication, such as total phosphorus. All measured stream water quality variables showed some differences among ecoregions. The results of these assessments are being used to establish different lake quality goals for several of the ecoregions.

Traditionally, an enumerative process has been used to identify and quantify the extent of water quality problems. As practiced, this process lacks statistical rigor in that the status of the resources cannot be specified with known precision. Alternatively, statistically sound survey designs were developed for the U.S. Environmental Protection Agency's National Lake Survey and National Stream Survey projects in order to assess surface waters relative to acidic deposition. A regional approach formed the basis for the survey design, and was incorporated into the subsequent synthesis and interpretation of monitoring data. Several levels of geographic stratification into regions of greater homogeneity increased sampling efficiency and allowed estimates to be made with known precision. In addition, having a regional framework prior to selecting sample sites helped determine the allowable coarseness of the sampling frame, so that sites were not located so far apart that important environmental conditions were unrepresented in the data set.

METHODS AND EXAMPLES OF REGIONAL DELINEATION

Regionalization segregates environmental diversity by delineating areas within which spatial variability is less than that occurring in a larger area. Regions can be delineated at any level of resolution and customized to suit a variety of management aims. The quality of a regional framework is influenced by the way the regions are delineated and the choice and quality of information (e.g., maps) used to delineate them. Important considerations for the development and use of any regional framework are its resolution and thematic specificity, and the nature of regional boundaries.

a. **Resolution** refers to the amount of detail represented or the degree to which the regions distinguish patterns at various map scales. Regions delineated at a national scale may not have enough resolution to address many issues at a state level, whereas regions at a state level may contain too much detail to be useful at a national level.

b. **Thematic specificity** refers to the degree of focus embodied by the regions. Regions may be very specific, such as those representing concentrations of alkalinity in surface waters, or very broad, such as those representing general patterns of ecosystem homogeneity.

c. **Boundary precision** varies across a regional map. Although boundaries are drawn as distinct lines on maps, they are actually transition zones of various widths. Some transition zones are as narrow as 2 or 3 km, such as along an abrupt interface between steep mountains and flat plains. Other transition zones are more than 75 km wide, reflecting a gradual transition from one region to another.

Methods

Two basic methods of regionalization involve quantitative and qualitative assessment techniques.

a. **Quantitative** delineation employs a statistical framework for analyzing data for the purpose of generating regions. Data are handled in a predetermined, systematic way, based on the initial expert judgment of the person designing the analytical classification scheme.

b. **Qualitative** delineation employs continual, interactive expert judgment for selecting, analyzing, and classifying data in order to generate regions. Judgments are based on the quantity and quality of the reference data and on interpretation of the relationships among environmental factors.

On first inspection, a quantitative approach seems most straightforward and replicative. However, quantitative tools are not sufficiently developed for incorporating the multivariate judgments needed to delineate regions. Because associations among environmental variables vary from area to area, as does the quality of the data representing those variables, and because regional changes often occur at geographic boundaries not explicitly detected by statistical point sampling frames, strict adherence to specified, quantitative interpolation rules commonly results in inaccurate interpretation of regions. Judgment should always be used when assessing the quality and quantity of data (numerical or mapped) for use in delineating regions.

With a qualitative approach, expert judgment is used to identify and select those factors that best define the regions in each area. Because factors important in one area may be unimportant for distinguishing regions in other areas, we believe that an "across-the-board" weighted overlay approach largely inhibits the ability to distinguish and make use of the most regionally prominent features. For example, a map of lake total phosphorus regions was recently completed for the Upper Midwest (Omernik et al. 1988). The map was compiled using multiple data sets and maps of factors believed to affect differences in lake phosphorus concentration. Delineation of the regions was based on patterns of the actual phosphorus values and their apparent associations with the other environmental factors. In some regions, phosphorus patterns appeared to be associated with Quaternary geology, whereas in others, soil type and vegetation cover, or some other combination of environmental characteristics, appeared to correlate better with phosphorus.

Examples

Certain regional frameworks have been widely used for a variety of resource management evaluations, including purposes for which they are poorly suited. There is nothing inherently improper in using an existing framework for resource inventory and management, but its utility should be evaluated relative to the availability of another framework, or the need to develop a framework for the specific purpose. Some frameworks reflect a narrow thematic focus. Maps depicting hydrologic units and physiographic regions are two of the more popular examples.

a. **Hydrologic units** are necessary for tracking the contributions of base streamflow and surface runoff to total streamflow and constituent loadings. They have also been used as cataloguing units to report water quality, with misleading results. Often, water quality in the headwaters of a unit is significantly different from water quality downstream because landscape features affecting water quality change dramatically. A regional framework that accounts for environmental factors affecting water quality would provide more rational accounting units.

b. **Physiographic regions** based strictly on land-surface form or physiography reflect the spatial patterns of some environmental variables for some parts of the country; but physiographic regions are not useful for understanding patterns in resource quality within large expanses of relatively homogeneous land surface types, such as in extensive plains or deserts.

Other frameworks have been compiled to depict regions based on a more general thematic focus, reflecting several environmental attributes. Three examples are *Land Resource Regions and Major Land Resource Areas of the United States*, *Ecoregions of the United States*, and *Ecoregions of the Conterminous United States*.

a. **Land Resource Regions and Major Land Resource Areas of the United States** was originally compiled by Morris E. Austin (1972). Depicting two levels of regional hierarchy, the map was intended to provide a geographic basis for management of agricultural concerns. Two factors affect the utility of the map: (1) individual states and groups of states, working independently with little or no quality control for consistency in delineation, compiled the map, and (2) delineation was largely based on information from soil maps of variable quality.

b. **Ecoregions of the United States** was compiled by Robert G. Bailey (1976). Depicting several hierarchical levels of regions, the map was developed for resources managed by the U.S. Forest Service. The delineation of regional boundaries was based primarily on a single environmental variable at each level of the hierarchy. Difficulty in using the map can result because the particular variable represented at each hierarchical level may not be consistently useful in determining resource conditions from one area to the next.

c. **Ecoregions of the Conterminous United States** was compiled by James M. Omernik (1987a). The map was developed to classify streams for water resource management and was based on the premise that regional patterns of combinations of environmental factors would be reflected in regional patterns in surface water quality. The map depicts one level of regional hierarchy. Regional boundaries were derived by examining the spatial distributions of a number of mapped environmental factors, most notably, but not limited to, land-surface form, potential natural vegetation, soils, and land use. The single hierarchical level depicted on the map may not provide the level of resolution required by many resource managers in many states, although additional levels of hierarchy have since been developed. Also, because the regions were delineated by considering the general effects of terrestrial and climatic characteristics on surface water quality, the map may not be appropriate for some terrestrial assessments.

THE PROCESS OF REGIONAL DELINEATION

The method of regionalization employed at the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon, has not only been used to delineate *Ecoregions of the Conterminous United States*, but also broader theme, lower resolution regions, for national-level management concerns and specific, higher resolution ecological subregions, for state-level management concerns. An example of a project addressing the latter is included in this report (Subsection 2.4.2). The following steps outline the general process for regionalization:

a. Define the scope of the project, set reasonable priorities, and decide on outputs (products). These important decisions place bounds on the types of reference material gathered, the environmental features examined, the level of resolution, and the geographic extent of the effort.

b. Collect reference maps, narrative descriptions, and data concerning the environmental factors relating to the regionalization objectives.

c. Identify the environmental characteristics predominating over an area and tabulate these characteristics to define prospective regions. Some regions will have a specific set of features; others will consist of a mosaic of characteristics too small to be separated at the selected resolution.

d. Outline the regional boundaries by circumscribing the mapped sets of characteristics tabulated in step c. Areas of uncertainty will occur where two regions abut and the landscape contains characteristics common to both. Expert judgment is required for delineating these transitional zones.

e. Generate a final map and regional descriptions.

f. Evaluate the regions using other data.

EVALUATION OF REGIONAL FRAMEWORKS

The value of an ecoregional framework lies in its utility in accounting for spatial variability in environmental resources. If variation within regions is as high as variation among regions, the framework is of little use. Thus, ecoregions have been evaluated through comparisons with spatial patterns in environmental data to assess the extent to which the regions accounted for the spatial variability of different variables. Our assessments were conducted in and with five states interested in evaluating and using our ecoregion framework.

Options for Evaluating Environmental Patterns

One option for evaluating regional patterns is to design and execute a sampling program tailored to the regions and variables of interest. Designing a sampling network with the specific intent of evaluating or characterizing regions has many advantages including:

- Control of geographic distribution of sites to insure broad spatial coverage and regional representativeness.
- Control of the timing of sampling to assess critical times of the year for a synoptic survey, or of the monitoring frequency for longer term coverage.
- Selection of variables of interest, either univariate for the development of specific theme maps, or multivariate, including water chemistry, physical structure, and biological variables.
- Assurance of completeness so that all variables are measured at the desired locations with the desired frequencies; data gaps cause problems when multivariate procedures are used.
- Specification of data quality objectives and quality assurance/quality control procedures so that data of known quality are obtained.

Another approach is to use existing data available from a variety of sources. Use of available data offers several potential advantages:

- Large numbers of sites and samples
- Historical perspective
- Great diversity of variables
- Relatively low costs (access to database and analysts' time)
- Short turnaround time between research design and execution of analyses

However there are also serious limitations to consider:

- Site mislocations and miscodings can be extensive.
- Data quality may be lacking or unknown.
- Distribution of sites may be inadequate.
- Sampling and analytical procedures may differ among data sets because different agencies collect, analyze, and report data for different reasons, at different times, using different methods and reporting units.
- Sites may lack complete sets of variables.

For example, in a project designed for the study of stream water quality in Colorado (detailed in Subection 3.6.1), we acquired existing data from some 5,000 stream sites in Colorado, but were only able to use 1% to 20% of the sites in our various analyses.

Analysis Techniques

Regardless of the data acquisition method, there are many useful analysis techniques for evaluating regional patterns. Emphasis is on presenting a picture of the spatial patterns and includes the use of:

- Color-coded dot maps to display spatial patterns in individual variables
- Box plots, by region, to display central tendency and variation
- Ordinations of chemical and physical habitat data and biological assemblages
- Indices that synthesize ecologically relevant information into a single number
- Regional species profiles

Statewide ecoregion evaluations (discussed in Sections 3 and 4) demonstrate patterns in biological, chemical, and physical variables corresponding to the regions in Arkansas, Colorado, Minnesota, Ohio, and Oregon. These studies used available data and data collected specifically for evaluation of the regions.

POTENTIAL APPLICATIONS AND FUTURE DIRECTIONS

The synoptic approach described in this report can be used to evaluate the extent and complexity of environmental issues and the benefits of applying regional analytical techniques. A number of themes currently of interest are described below. Because the combination of terrestrial and climatic information used to develop Omernik's ecoregion map is pertinent to several of the issues, the map may be useful as an upper-level framework.

a. **Cumulative Impact Assessment on Water Bodies.** The extent of effects on surface water quality from waterway modification, waste disposal, and terrestrial devegetation is essentially unknown. A regional framework can be used to organize and analyze environmental data to assess the cumulative effects of these management practices. Three types of assessments could be considered: attainable quality, current status, and best management practices.

b. **Nonpoint Source Pollution.** Evaluation of nonpoint source pollution on surface waters is closely related to the study of cumulative impacts. Effects on surface water quality from modification of water courses, irrigation return flow, terrestrial devegetation, stockyard manure dispersal, and chemical agents can be sorted through regional analysis of representative surface waters. A regional framework can be used to organize and analyze environmental data to assess the isolated and combined effects of various management practices.

c. **Soil Erosion.** Our agricultural soils are threatened by long-term loss of fertility from erosion due to management practices related to farming, timber harvest, livestock grazing, and urban and rural development. Soil type, slope gradient, slope aspect, potential areas of mass soil movement, and water courses can be mapped and compared with irrigation patterns and intensity, tilling practices, forest and range vegetation condition, and rates of soil erosion. Such information can be used to determine best tilling practices, timber harvest locations and levels, timing and intensity of grazing allotments, and best locations and associated practices to minimize impacts from construction.

d. **Endangered Species.** Risks to threatened, endangered, keystone, and game species from pesticides can be evaluated by examining maps of known and potential habitats of the species of concern in concert with maps of pesticide application patterns. Potential pesticide dispersion can be estimated by geographic assessment of drainage patterns and soil characteristics. Acute direct effects and chronic indirect effects on species of concern can be assessed by field studies of areas expected to differ in impact. Potential areas for introduction or restoration of game or endangered species can be evaluated for suspected pesticide stress.

e. **Biological Diversity.** Local and regional patterns in environmental variables affect biodiversity and the impact of human actions on diversity. Habitat types or regions that are particularly rich in species, have great abundances of individuals, or support unusual communities with high rates of endemism can be mapped. Regional analysis of biogeographic and habitat data can be compared with species distributional patterns and abundance so that, where habitat conditions are desirable, managers can seek to increase those conditions on a regional scale; where conditions are undesirable, managers can attempt to reverse those trends, protect critical remnant ecosystems in the region, or expand or reconfigure refugia before species become threatened or endangered. Environmental characteristics common among habitats or regions can be used to develop resource management policies that are more protective of biodiversity.

f. **Groundwater Assessment and Protection.** Groundwater aquifers may become contaminated by nonpoint sources of pesticides and fertilizers, naturally occurring chemicals, and point source toxics. Natural features, anthropogenic contributions, and human consumption can be spatially assessed to predict the relative risk of contamination of groundwater with respect to drinking water and wellhead protection. Another related concern is hazardous waste siting and assessment. Proximity of proposed and existing sites to human settlements, ranges and migratory pathways of species of interest, surface drainage patterns, and surface waters and wetlands can be incorporated into the regional analysis.

g. **Global Climate Change.** The effects of global climate change on crop production, human welfare, and biota may be predicted from regional geographic analyses. An analysis of current soils, potential natural vegetation types, land-surface forms, and climates has led to the delineation of Omernik's (1987a) ecoregions. Current species ranges, human population centers, and patterns of crops, forage, and forests can be analyzed in comparison with ecoregions to document present distribution. Quantitative variable response models can be developed to predict the distribution of variables under different scenarios. The reduction or increase in the predicted range of a particular species under various scenarios offers a quantification of the possible changes. Projected climates and predicted species ranges can be mapped to study the shift of the less stable variables over the more constant environmental characteristics.

SECTION 1

THE CONCEPT OF REGIONS

1.1 INTRODUCTION

All of us are familiar with different kinds of regions at different levels of resolution. We recognize political regions, perceiving the world as a hierarchical set of units: continents comprising countries comprising states, counties, cities, districts, and neighborhoods. We recognize cultural regions. We identify people by their appearance, mannerisms, and speech patterns. We can often tell if they hail from one part of the United States or another, or if they come from our home state or city, uptown or downtown.

In a more formal sense, a region is associated with a specific location that covers some extent of area and contains a certain degree of homogeneity with respect to the characteristics used to define it (deBlij 1978). Wiken (1986) explained that, "Regionalization is a method of reducing or eliminating details which do not, on the average, hold true over large areas," and Hart (1982) stated:

> A region is a more or less homogeneous area that differs from other areas. To use a more contemporary jargon, within-region variance is less than between-region variance. The *best* regions are those that are based on the greatest amount of interrelatedness.

Hart further noted that the concept of *region* is a useful intellectual device for organizing and presenting information and promoting communication.

A type of region commonly used in describing surroundings and conditions is the environmental region. We speak of the *banana belt*, the coniferous forest zone, and the Great Plains. We examine world biomes, the ecosystems within them, and the smaller habitat types within the ecosystems. The process for delineating environmental regions continues to evolve. The term *ecoregion*, originally coined by Crowley (1967) and first carried to mapped form as a classification of ecological regions of the United States by Bailey (1976), has become generally accepted to mean a region of relative homogeneity in ecological systems or in relationships between organisms and their environments (Omernik 1987a). However, efforts to delineate natural ecological regions for the United States date back to the early part of the twentieth century (Joerg 1914), in response to a general interest in studying distributions of environmental phenomena (Herbertson 1905).

In many environmental resource agencies, interest today centers on environmental regions and research and applications pertaining to ecosystem management. Recent legislation (Clean Water Act, Public Law 92-500, 18 Oct. 1972 and numerous amendments; National Environmental

Policy Act, Public Law 91-190, 1 Jan. 1970 and several amendments) requires that reports be submitted to Congress on the condition of national resources, prompting agencies to explore more effective ways of reviewing, managing, and reporting on resource concerns through recognition of the environmental components most affecting, or affected by, those concerns. Many government agencies have already developed regional management structures to address these needs, but others remain bound to political boundaries as management units. We believe that frameworks that divide or classify natural resources into relatively homogeneous units (regions) can provide a tool to accelerate and improve the processes of resource assessment, management, and reporting.

1.2 PURPOSE AND SCOPE

The purpose of this report is to explain the concept and nature of regions and the utility of a regional framework for resource management. In particular, this report includes discussions on (1) the nature of regions and boundaries, (2) some of the more popular regional frameworks, their attributes, and their limitations, (3) the synoptic regionalization approach developed at the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon, and examples of surface water projects where the approach was applied, (4) the process of selecting regionally representative reference sites, (5) methods of analyzing data from such sites for extrapolating results to larger areas, (6) ways in which an ecoregional framework has been applied toward state and national level assessments of resource quality, for example, to establish physical, chemical, and biological resource criteria in accord with regional capacities for buffering environmental changes, and (7) other possible areas of research and management that might benefit from regional assessment techniques.

Discussions in the report are divided into four main sections. Section 1 covers some major components of regional representation, including resolution, thematic specificity, and boundary accuracy (Section 1.3); utility of frameworks for selection of regional reference sites (1.4); principal factors contributing to the delineation process, mainly relating to reference materials used and approaches taken in delineation (1.5); and examples of popular regional frameworks, their attributes, and their limitations (1.6). Section 2 introduces the approach used by the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon, to develop environmental regional frameworks for research and management, including the circumstances behind the development of the approach (2.2), the methods developed (2.3), and specific examples using the methods (2.4). Section 3 presents methods for evaluating correspondence between regions and patterns in other environmental data and incorporates discussion on data sources (3.2); data needs, such as type, quality, and quantity (3.3); regional sampling options (3.4); and methods of regional data analysis (3.5 and 3.6). Section 4 relates the applicability of regional analysis for addressing state and national management mandates related to water quality standards (4.2) and water body monitoring, assessment, and reporting (4.3), and briefly describes additional fields of potential application of a regional approach (4.4).

Throughout this report, we use figures and tables from specific projects relating to regional assessment of resources. Three maps (plates) pertaining to descriptions of a recent study of environmental regions in Colorado are located in an envelope inside the back cover. In the front part of the report, we include a list defining our usage of terminology in an attempt to reduce ambiguity resulting from interpretations unique to different disciplines. Because of their prevalence throughout this document, four terms are defined in the following paragraph.

To impose some consistency in the terms used to describe regionalization, we have divided the process into four main phases. The act of initially tabulating (listing) the major environmental features of potential regions is termed *defining* regions. Physically drawing the regional boundaries is termed *delineation*. Following delineation, a final map is drawn to *depict*, or show, the regions. To complete the process, regional *descriptions* are composed to characterize the regions in more detail than the initial tabular listings.

1.3 FACTORS AFFECTING REGIONAL REPRESENTATION

Before discussing regionalization, we should mention several aspects of mapped regional frameworks that affect their suitability for use in resource assessment. These include their level of resolution, degree of thematic specificity, and precision of regional boundaries and descriptions. The level of resolution shown on a map relates to the level of detail incorporated, or the ability to distinguish patterns at various scales and for various purposes. Thus the resolution affects the suitability of the map, or framework, for different uses. For instance, in planning and carrying out a successful automobile trip across the United States, several levels of resolution are needed: a small-scale road atlas to help determine the general course of the trip, larger scale state maps to determine the best routes to travel, and even larger scale street maps to locate specific streets and addresses. To attempt the trip relying solely on the resolution portrayed on one map would be inappropriate. The route is more easily and accurately located when the amount of detail portrayed is appropriate to the need.

In the context of resource assessment, frameworks of different resolution suit different management concerns and increase the efficiency and accuracy of evaluations. At a national level, it may be effective to examine environmental patterns from a more distant, general perspective, comparable to studying patterns on the earth from an altitude of about 30 km above ground. For refinement of these patterns, such as in examining a single- or multi-state area, increasing the resolution to patterns discernable at 10 km (a common cruising altitude of commercial jets) above the ground might be useful. If the patterns must be further sorted, information of a greater resolution may be obtained by viewing the earth's resources from closer distances, or even from the ground. Appropriate resolution is thus dictated by the goals of regionalization: broad-scale regions for coarse level needs, and finer scale regions for more detailed needs.

Another aspect of regional frameworks is their inherent degree of thematic specificity. Some regional themes are broad-based and appropriate for a large variety of uses; others are very specific and have a much narrower range of utility. The military uses general purpose regions, for example, to analyze broad-scale operation scenarios for entire countries. Military geographers define broad regions within which combinations of conditions such as climate, topography, soils, and vegetation are similar. Information on a variety of geographic phenomena, predominantly in mapped form, is used to determine these regions. For specific needs, such as determining suitability for air landings or concealment of troops, more specific information about local topography, surface material, and vegetation type and density is used and the resulting classification framework has narrower applications.

In environmental studies, regions may represent broad similarities in ecosystem components (e.g., Bailey 1976; Herbertson 1905; Joerg 1914; Omernik 1987a; Udvardy 1975; Wiken 1986), or they may be designed to address more specific themes, such as vegetation types, land-surface forms, soil nutrient concentrations, or hardness of surface waters. The regions based on broader themes can be used for a variety of terrestrial and aquatic surveys and inventories; those based on narrower themes are useful for studying how the distribution of the single feature affects, or is affected by, other environmental characteristics. Because the management of water resources often concerns a variety of environmental attributes and issues, maps of broader thematic regions are of greater utility for such purposes; they correlate with a wider variety of environmental characteristics.

A third aspect of regional frameworks is that regional boundaries and descriptions are not discrete. Regional boundaries represent zones of transition on the ground, where the characteristics of one relatively homogeneous area blend with those of another. The transition width of some boundaries is very narrow and recognizable from the ground; for others, it is less distinct and can best be distinguished from a distance. A person riding in an automobile across one of these fuzzier boundaries would not be able to tell when the boundary had been crossed. However, to a person whose eyes were closed 50 km before crossing the *line* and opened 50 km beyond, the regional differences would be noticeable.

It is also important to recognize that regional boundaries cannot be reliably transferred from a small map scale to one of larger scale using mechanical means (i.e., following political borders or geographic reference points common to both maps). For example, if the national (1:7,500,000) ecoregion map (Omernik 1987a) is enlarged to the scale of a U.S. Geological Survey topographic map (1:250,000), the resulting boundaries will appear on the order of 8 km wide. Because it is not acceptable to work with such a wide line on the topographic map, we refine the line using higher resolution reference maps similar in content to those used to define the initial, smaller scale ecoregion boundaries. Thus, the appropriate way to transfer lines to maps of other scales is not through mechanical means, but through examination of maps of appropriate resolution in detail with respect to environmental characteristics discernable at the new map scale.

Just as variation in environmental features limits the precision of regional boundaries, variability of features within regions limits the precision of regional descriptions. The descriptions represent the characteristics typifying each region, but it is inappropriate to assume that all areas within a region possess all typifying characteristics. As Wiken (1986) reminded us, there are regional details that generally do not hold true over large areas. Still, regional descriptions help in conceptualizing the representative qualities as a basis for recognizing a region's distinction from surrounding areas.

1.4 REGIONAL REFERENCE SITES

One of the benefits of a regional framework is its use in selecting regional reference sites. Since a framework provides boundaries around areas within which environmental conditions are relatively homogeneous compared with other areas, sites comprised of these conditions can be used as references for other, environmentally similar sites. An essential component of reference site selection is its representativeness in a region; it is feasible to map the extent of similar conditions to specify the areas within which reference sites can be selected and over which reference site information is expected to apply. General guidelines for selecting regional reference sites are:

a. Identify the objectives and the combination of environmental characteristics that most pertain to the objectives.

b. Map areas where these combinations occur and select sites within these areas.

d. Eliminate sites that are physically or legally inaccessible.

e. Check the accuracy of mapped information using current aerial photographs, site visits, and local expert opinion to eliminate sites not meeting selection criteria.

f. Collect data from remaining sites for analysis.

It will be necessary to modify or expand these guidelines for individual purposes. For example, if the objective is to measure regionally attainable stream quality, the above process would be somewhat modified. For this example, it is assumed that attainable quality can be approximated by measuring physical, chemical, and biological quality of streams draining watersheds that are representative of the natural environmental characteristics typifying the region and subject to the least possible amount of human influence. Thus the following steps apply:

a. Of the characteristics typifying the region, specify those that have an effect on water quality, such as regional soil type, vegetation cover, amounts and intensity of annual or seasonal precipitation, gradient of land-surface forms, and occurrence of natural geologic deposits.

b. Map areas that share a similar combination of characteristics.

c. Select watersheds from within those areas.

d. Eliminate watersheds where access is prohibited.

e. Eliminate watersheds affected by human influence. If there is an insufficient number remaining, add watersheds subject to the least amount of influence. The resulting set of sites will rarely contain any pristine watersheds. However, given current regional land use practices, this collection of watersheds should yield information on what is reasonably achievable within that region. In some regions, all watersheds are subject to moderate to severe use impact. Thus, sites that are moderately disturbed are the closest available approximation to natural conditions. For example, in a region used extensively for farming, the least impacted, environmentally representative watersheds might be those having thin, discontinuous strips of natural riparian vegetation along unchannelized stream reaches.

f. Perform field checking for site suitability before sampling to insure the accuracy of mapped information and to eliminate inappropriate watersheds. Current low-altitude aerial photographs and local expert opinion may be used as initial screening methods; site visits are essential.

g. Collect physical, chemical, and biological data from the sites remaining on the list to generate the reference data that define the range of regionally achievable quality against which the quality of other sites can be compared.

An important reason for identifying regions is that information from areas within a region can be extrapolated to other parts of the region (e.g., water chemistry measurements of within-region reference streams being used to infer stream water chemistry throughout the region). Thus, a major assumption is that the drainage area of the streams being measured exhibits the same characteristics as the drainage areas for which water quality is being inferred. The value of the extrapolation hinges on careful selection of representative sites.

1.5 FACTORS AFFECTING THE DELINEATION OF REGIONS

The *concept of regions* has developed because of our need to study, describe, and communicate spatial information. *Delineation* translates the concept of regions into a tangible result, or map. The outcome of the regionalization process is not only affected by the management or research objectives, but also by the origin, quantity, and quality of references used to delineate regions. References may include maps, numerical data, or interpretive text. Because we primarily use maps in delineating regions, this discussion focuses mainly on maps.

1.5.1 Origin of Regional Reference Maps

Some regional frameworks have very narrow objectives (specific themes) and are commonly delineated using single sources of data. Precipitation maps, for example, rely on rain gauge measurements from scattered weather stations. Point data are interpolated to project continuous categories of precipitation over the landscape. Physiographic maps are derived from photo or satellite imagery. Map units generally require less interpolation than point data, but remote imagery can be difficult to interpret because diurnal, seasonal, and annual changes in environmental conditions greatly vary the appearance of land characteristics on imagery. Dependency on a single reference source can lead to gross misinterpretation where insufficient coverage or quality of information occurs.

In cases where few data are available for the variable of interest, regions are sometimes classified using a surrogate variable known to be related to the variable of interest. For example, regions depicting the sensitivity of surface waters to acidification have sometimes been delineated by classifying a soil or rock type, based on known relationships between that characteristic and surface water sensitivity (Environment Canada 1987; Hendrey et al. 1980; McFee 1980). Interpretation of surrogate variables is complicated by potential problems with quality and quantity of data, and by the fact that the relationship between the two variables may not be consistent across the country due to the effects of other environmental factors.

Some regions are delineated based on synthesis of a number of mapped environmental variables; there are several benefits to this method of regionalization. Because environmental characteristics are interrelated (e.g., climate and surficial geology affect soil formation; soil formation and climate affect vegetation type, which further affects soil formation; all of these factors affect land use, and land use affects vegetation succession and soils), spatial distributions of many of the features coincide, reinforcing patterns that would not be entirely identifiable from any single variable. The mapped distributions of each can be compared to gauge their relative validity. Where distributions in all but one mapped factor tend to follow similar patterns and appear to explain the distribution and/or quality of a variable of interest, the reliability of the aberrant factor can be questioned. For example, a particular soil type may well be associated with differences in the condition of a particular variable, but the map of soil type distributions may be of poor quality or the classification used may be inappropriate for revealing the spatial relationship with the variable. Thus, the usefulness of a complementary set of references compensates for the potential problems in quality encountered from a single data source.

1.5.2 Quality and Resolution of Reference Maps

Variation in the quality of maps used in regional assessment has a considerable bearing on the relative accuracy or utility of the resulting regions, so screening is necessary for all types of regional assessment. The accuracy of base data, the manner in which the data are evaluated and interpolations made, and the appropriateness of the classification scheme to the purposes of the regional assessment all affect the quality of the regional classification. Reference maps are derived from a variety of sources. The accuracy of some maps is substantiated by ground-truthing, but this is not often the case. Some maps are derived primarily from analysis and interpretation of numerical data (e.g., climatological isoline maps), some from interpretation of aerial imagery (e.g., land-surface form and land use maps), some from historic information (e.g., maps of natural vegetation and species ranges), and some from existing maps (e.g., environmental regions). Many maps are the product of a combination of sources (e.g., maps of potential natural vegetation, typically assembled from historic accounts, imagery of present distribution, and an array of maps, including those showing existing climate, soils, and landforms). If several reference maps are being used for delineating regions and one of the maps has been closely derived from another, then the most recent map does not really depict additional information, but somewhat duplicates its predecessor. Soils maps, for instance, are often assembled from relatively few data points and inferred associations with mapped vegetation and physiographic features.

The method of evaluation and compilation of numerical, mapped, or interpretive data varies not only from map to map, but within each map as well. Where data are faulty or lacking, or where inappropriate cartographic techniques have been used, the distribution of an environmental variable on one map may bear no resemblance to the distributions of related variables on others. Also, if different portions of a map have been compiled by a number of persons working independently, there are likely to be problems with the consistency of detail presented and interpretation methods followed. These are good reasons for using a complement of maps to aid in regionalization. If one map fails to display suspected distributional patterns for an area, other maps of related characteristics may display distributions from which to infer the appropriate patterns.

A major consideration in evaluating references is how pertinent they are to the regional assessment goals. Some references have misleading qualities that adversely affect the regionalization process. For instance, remote sensing imagery is often used for delineating regional patterns of environmental resources. Yet, because of spatial, diurnal, seasonal, and multi-year variation in environmental conditions, the imagery appearance of specific characteristics such as vegetation, soils, and land use varies. Maps of environmental characteristics should be used to complement remote sensing imagery, and extensive field verification of the study area is often required to avoid misinterpretation of patterns.

In some cases, the name of a reference map is misinterpreted to imply a theme wider than the framework designers intended. A map of hydrologic units (U.S. Geological Survey 1982a), for example, is assumed by many map users to imply units that relate to surface water quality and, at the very least, to topographic drainages. In actuality, hydrologic units are management cataloguing units that are based somewhat on surface hydrologic basins, but correspond poorly, if at all, to patterns of factors that cause spatial differences in the quality and quantity of surface waters. To evaluate the utility of these and other reference maps, it is important to understand the meaning of the map units.

Resolution of detail on the reference maps affects the level to which regions can be defined and delineated; regions cannot be delineated in greater detail than that provided on the reference maps. Map scale should not be confused with level of detail portrayed. Maps of two different characteristics compiled at the same scale are likely to reflect different levels of detail or generalization. For that reason, it is not necessary for reference maps to be at a uniform scale to be useful for interpreting and delineating regions. Differences in resolution must be mentally accommodated for when patterns are compared from map to map.

There are a few ways to determine the level of resolution represented on a map. The amount of irregularity or apparent detail in the map unit boundaries is not necessarily indicative of the level of information represented.. Comparisons between a particular reference map and several others at the same or a larger map scale can provide some indication of the relative degree of detail portrayed. Accompanying text may describe the compilation sources and methods. Boundaries around map classes having a stairstep or sawtooth appearance indicate the map has been compiled from information at the resolution of a single *step*, or cell. The cells may represent a summation of information from larger scale maps or remote imagery, or may result from the coarse resolution capacity of computer hardware or software.

1.5.3 Approaches to Delineating Regions

One way to categorize delineation methods is to distinguish quantitative from qualitative compilation methods. By *quantitative*, we mean employing a statistical framework for selecting, analyzing, and classifying data to form regions. This implies that all reference data must be handled in a predetermined, systematic way, and normalized for analyses. By *qualitative*, we mean expert judgment applied throughout the selection, analysis, and classification of data to form regions, basing judgments on the quantity and quality of reference data and on interpretation of the relationships between the data and other environmental factors.

On first consideration, a quantitative approach seems a straightforward, replicative method for planning, programming, and documenting regional analysis. Still, there is variability in results simply because of the variety of ways that data can be manipulated, depending upon the judgment of the analyst, and because quantitative tools are poorly developed for incorporating the multivariate judgments involved in delineating regions. Evaluations are continually needed to filter out variations in quality and quantity of reference information for different areas and different associations between environmental variables. Furthermore, regional changes often occur at geographic boundaries not explicitly detected by point sampling and interpolation schemes.

Quantitative methods appear most appropriate for addressing specific regional themes for which spatial coverage of source data is good, but even in seemingly straightforward cases, qualitative decisions are necessary. For example, precipitation maps, depicting areas within which a particular amount of annual rainfall and/or snowfall can be expected, are based on mathematical interpolation of measurements taken at numerous weather stations over a period of years. Qualitative judgments are needed to amend interpolations and account for the effects of local terrestrial features on weather circulation patterns for areas where data are lacking. When quantitative methods are strictly adhered to, interpretation of data can result in improper regional inferences. Omernik et al. (1988) describe a scenario in which a nutrient-rich, agricultural lake plain, containing few lakes (none with data), is bordered on three sides by forested areas of pitted glacial outwash and moraine containing many lakes of low phosphorus concentration. Quantitative techniques would probably overlook the agricultural lake plain, including it in the class of phosphorus values assigned to the surrounding forests, a class whose values would probably be much lower than those expected for the lake plain.

The strength of a qualitative approach is that all available data, including spatial patterns of the variable itself, maps of characteristics that cause or reflect regional variations in the quality of the variable, and expertise of local and regional managers and scientists, can be incorporated to define and delineate regions. References that are meaningful for explaining the distribution or quality of a variable in one location may not be helpful in another because of interactions with still other environmental factors; with a qualitative approach, reference sources can be applied or discarded based on their applicability to developing an understanding of the spatial distribution of the variable. For example, gradient and watershed size may be the most important environmental factors influencing stream water quality in a steep mountainous region, but less important than the effects from soil erosion and farm chemical runoff in a downstream, flat, agricultural region. A qualitative approach encourages selection of the most appropriate array of references to assess patterns region by region. The drawback of a qualitative approach is that two different investigators are not likely to arrive at identical regional boundaries. However, it is also unlikely that two independent investigators would delineate the same set of boundaries from a quantitative approach because of the qualitative judgments necessarily involved, such as choosing which reference data, weightings, and classification techniques to use.

Using a qualitative approach, it will become apparent which mapped environmental features most relate to variables of interest, and to what extent. A recent study illustrating this point is a map of lake total phosphorus regions for the Upper Midwest (Omernik et al. 1988). The map was developed for lake management with particular regard to eutrophication. This phosphorus map was compiled using multiple data sets, screened for comparability, and all available maps of factors believed to affect differences in lake phosphorus concentration, including Quaternary and bedrock geology, soils, existing and potential natural vegetation, land use, and physiography. The regions were delineated based on patterns of the actual phosphorus values and their apparent associations with the other factors.

Some researchers suggest that a weighted overlay method represents a middle ground between quantitative and qualitative methodology. Such a method requires that environmental characteristics be ranked in importance over a definable area so that the rest of the delineation process remains more objective and replicative. If this could be accomplished, regionalization procedures could be carried out using computerized geographic information systems. We remain unconvinced of this possibility for a number of reasons:

a. The relative importance of particular environmental characteristics for influencing the areal definition of a particular region commonly varies throughout the region.

b. Even if the relative importance of the environmental characteristics remained constant across a region, the quality of information portrayed on the reference maps used for establishing the areal extent of the region often varies significantly, requiring continual modification of delineation techniques. The reasons for this variation in quality result from the different source materials and base maps used to compile individual reference maps. Thus, the level of data generalization not only varies among different maps of the same scale, but within an individual map as well. This affects the accurate portrayal of information relative to its true geographic location, so it is necessary to manually adjust the placement of regional boundaries so as to avoid the "slivering" that would result from mechanically overlaying a set of maps.

c. Because of the inconsistencies mentioned in the previous two points, there is no way to pre-assess the decisions that will be required to draw regional boundaries. Preassessment is necessary for designing regionalization computer software.

d. The above reasons aside, the amount of computer storage space required for all the digital information comprising the reference maps would be prohibitive.

We feel it is necessary to actually complete the process of drawing regional boundaries in order to know what decisions will be required for creating comprehensive computer software capable of performing regional delineation. We also believe that the number of discussions and judgments involved in synoptic regionalization preclude the design of a computer program able to account for even a small portion of the possibilities that might occur. Attempting this would increase the difficulties of the regionalization process manyfold. Computer technology is much too primitive for this type of analysis.

1.6 EXAMPLES OF ENVIRONMENTAL REGIONS

1.6.1 Maps Depicting Specific Environmental Characteristics

A number of maps depicting environmental regions have been developed as a result of interest in a particular resource or issue. Maps showing regions of geology, land-surface form, soils, vegetation, land use, physiography, hydrologic drainage areas, lake phosphorus concentrations, and sensitivity of surface waters to acidic deposition are several examples. These maps are useful for a variety of assessments, assuming the map units have been compiled in a manner appropriate for the intended use. The units represent areas within which certain classes or types of environmental characteristics are expected to predominate. Certain of these maps have been widely used as frameworks for resource investigation, management, and reporting. Because the frameworks were published and available, had map units useful for explaining some patterns of environmental phenomena in some parts of the country, or had framework titles relating to a particular resource, they were applied to a number of uses, some for which they were neither intended nor suited; hydrologic units and physiographic regions are two examples.

The hydrologic unit framework of the U.S. Geological Survey (1982a, 1984) is probably the most widely used of the regional frameworks. Though not exactly the same as basins, hydrologic units are similar, in that their boundaries are often based on topographic drainage divides. A number of water resource management activities, such as flood forecasting, require this type of framework for tracking the contributions of streamflow and precipitation runoff to total streamflow at any point downstream in a basin. However, there is a tendency to use basin and hydrologic frameworks to summarize ecological data. Because hydrologic units are based on topographic drainage contours and political management needs, rather than on characteristics that control surface water quality, the units contain a considerable mix of vegetation, soils, land-surface form, and land use characteristics. Thus, data from more than one environmental region are aggregated within each framework unit.

A specific example of this situation is a set of maps compiled to illustrate violations of national standards for fecal coliform, dissolved oxygen, and total phosphorus in United States streams (Council on Environmental Quality 1979). The data were obtained at or near the mouths of major rivers and their principal tributaries. The quality measured at each sampling point was projected to its entire upstream basin, though the environmental characteristics impinging on the upper portions of the watersheds did not usually reflect those at the sample site locations. A case in point is the Willamette River Basin in Oregon. More than half the streams in the basin and 95% of the summer streamflow originate in the Cascade Mountains and have extremely low phosphorus levels. Streams draining the valley portion of the basin have fairly high levels of phosphorus, due to rich valley soils, agricultural land use, and higher population densities. To extrapolate basin-wide water quality information from any one sampling point on the river is misleading.

Also popular with resource managers and researchers are frameworks derived from physiography. Of these, Fenneman's (1946) has probably been used most often, for example, by the National Park Service, in its National Natural Landmark Program (Iffrig and Bowles 1983), and by state and local management agencies and researchers. Like other regional frameworks dependent on single characteristics, physiographic regions do reflect regional patterns of certain environmental resources for some parts of the country. But in areas of flatter terrain, where surficial geologic deposits, soils, land use, or vegetation are comparatively more diverse, physiographic regions are not useful for indicating spatial patterns in resource quality, except perhaps on a more local level.

Limitations to the utility of this framework also result from the criteria used to classify the regions in which some environmentally distinct areas are not recognized because of the particular way the author chose to classify them. The Sand Hills area in Nebraska, for example, is not represented on Fenneman's Physiographic Region map (1946), yet the area is a unique region of the United States, and is recognized on nearly all other national physiographic, soils, land use, and vegetation maps. This kind of problem is common when relying on frameworks based solely on classification of a single characteristic.

1.6.2 Maps Based on Combinations of Characteristics

In addition to maps compiled to depict particular environmental characteristics, maps have also been compiled to depict regions of a more general nature. In compiling these maps, researchers and resource managers have often considered a number of environmental characteristics to delineate these regions (Bailey 1976; Herbertson 1905; Omernik 1987a; Rowe and Sheard 1981; Wiken 1986). Two of the most commonly used national frameworks are: *Land Resource Regions and Major Land Resource Areas of the United States* (Austin 1972; U.S. Department of Agriculture 1981) and *Ecoregions of the United States* (Bailey 1976). Both frameworks incorporate hierarchical levels of resolution and have some utility for environmental resource management.

Land Resource Regions and Major Land Resource Areas (MLRA), originally compiled by Austin (1972), has undergone one revision (U.S. Department of Agriculture 1981) and is currently undergoing a second. The intended purpose of the MLRA map was to provide a geographic basis for making national- and regional-level management decisions about agricultural concerns, inventorying and determining research needs, extrapolating information from site specific research to other areas within the regions, and spatially organizing resource conservation programs. At the time of its compilation, the MLRA map was probably the best available framework for meeting these objectives. The continued developmental nature of this regional framework, and of regional frameworks in general, is illustrated by the subsequent recognition of the need for its revision.

Three factors in the MLRA compilation process weakened its utility as a management framework. First, although the delineation of the regions was based on a number of environmental characteristics, the work was heavily dependent on soils maps that, for many parts of the United States, particularly forested areas, were of low reliability. Second, the MLRA map represented a composite effort by individual states and groups of states working independently to compile information and delineate regions for different portions of the country (Dierking, pers. comm.). Method and resolution of regional interpretation were not consistent across the country. For instance, the Northern Lakes States Forest and Forage Land Resource Region, in the Upper Midwest, is divided into many small MLRAs, apparently based on very local geomorphic features rather than on distinct differences in overall land-surface form, soils, vegetation, or land use. On the other hand, the Willamette and Puget Sound Valley MLRA combines two valleys of very different climate, land-surface form, soils, vegetation, and land use. Finally, the regional hierarchy of the map is not discrete; a single MLRA may be assigned to more than one resource region. For example, the Southern Rockies MLRA (map unit 48A) is included in both the Western Range and Irrigated Region and the Rocky Mountain Range and Forest Region. This is the case for several of the MLRA map units.

Ecoregions of the United States was developed by Bailey (1976) to provide a hierarchical geographic framework primarily for environmental resources managed by, or of interest to, the U.S. Forest Service. The map was developed with a principal interest in the forested portions of the United States. Although Bailey considered patterns in climate, soils, vegetation, and land-surface form in compiling the map, his regional boundaries were fundamentally based on one particular characteristic (climate, potential natural vegetation, or land-surface form) at each hierarchical level of his classification. By relying on maps of single geographic factors for delineating regions at individual hierarchical levels, the quality of the resulting framework suffers where data from the specific factor are deficient, or where other factors have greater influence on, and thus may be more indicative of, environmental change. We tried to use Bailey's framework for sorting spatial patterns in stream quality (Hughes and Omernik 1981; Omernik et al. 1982), but when the classification was tested, the framework proved inadequate.

1.7 SECTION SUMMARY

In this section we have discussed (1) the concept of regions and the various aspects inherent in regional frameworks, including the level of resolution, thematic specificity, and boundary precision, (2) the use of frameworks for selecting reference sites in order to make inferences about the regional quality of resources, (3) the major factors affecting the delineation of regions, namely, the references consulted and the approaches followed, and (4) examples of environmental regions, commenting on their respective attributes and limitations.

In the next section, we describe the development of our regional framework and list and explain the steps used in regionalization. Two specific projects are detailed as examples of how the procedures have been applied at different levels of resolution.

SECTION 2

DEVELOPMENT OF *ECOREGIONS OF THE CONTERMINOUS UNITED STATES*

2.1 INTRODUCTION

In this section we trace the development of an environmental regional framework at the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon. A general explanation of the resulting delineation process that evolved from this experience is provided. Further detail of the steps involved is illustrated in the discussion of two specific delineation projects addressed at different levels of resolution. In the first project, ecoregions of relatively homogeneous environmental characteristics were delineated for the entire conterminous United States. In the second project, within-region variability was further sorted to derive subregions of the ecoregions intersecting the state of Colorado.

2.2 BACKGROUND

Development of *Ecoregions of the Conterminous United States* (Omernik 1987a) began through efforts to classify streams for more effective management of water resources. Initially, we tried to use the framework by Bailey (1976) and the MLRA framework (U.S. Department of Agriculture 1981), but found both frameworks inadequate due to the reasons described in Subsection 1.6.2. At this time, certain states were also realizing a need for a new framework to aid in managing water resources. This interest led to a joint effort initially with the states of Arkansas and Ohio (documented in Hughes and Larsen 1988; Larsen et al. 1986, 1988; Rohm et al. 1987; Whittier et al. 1987) in the development and evaluation of a regional management framework (see Appendix B). Later, projects were begun in Minnesota (Heiskary et al. 1987) and Oregon (Hughes et al. 1987; Whittier et al. 1988). To address management needs, it was important that ecosystem regions reflect similarities in the type, quality, and quantity of water resources, and the factors that impact them. We based the design of this framework on the observation that surface waters tend to reflect characteristics of the watersheds they drain (Beschta and Platts 1986; Karr et al. 1986; Warren 1979), which in turn reflect larger, regional patterns of combinations of environmental variables. These combinations vary spatially across the country, altering the importance of different variables in determining the character of each region.

After delineating ecoregions in Arkansas, Minnesota, Ohio, and Oregon, reference sites were selected for data collection and analysis (Sections 3 and 4) to evaluate the framework. Preliminary evaluation indicated potential utility in delineating ecoregions in a consistent way for the rest of the conterminous United States (Omernik 1987a). A national map was produced at a scale of 1:7,500,000 depicting one hierarchical level of regions. Multi-state maps, showing the same level of hierarchy, but in greater detail, were published at a scale of 1:2,500,000 (Omernik 1987b, 1987c; Omernik and Gallant 1986, 1987a, 1987b, 1987c, 1988). Other hierarchical levels of ecoregions are currently being developed, including a coarse level of aggregated ecoregions for national level resource assessment.

2.3 AN OVERVIEW OF REGIONALIZATION

One purpose of regionalization is to sort out spatial variability in environmental characteristics we wish to manage. In collecting and examining reference information for delineation of environmental regions, our aim is to understand as much as possible about the interest area: what it looks like, the driving environmental features, the kinds of natural and human impacts commonly influencing the resource quality, and the characteristics supporting the delineation of the area into regions. Each ecoregion is driven by different types of environmental features. Were we to rely on a single feature for regionalization, we would miss significant regional patterns in many areas. In delineating ecoregions, for instance, we find that land-surface form has a dominating effect on vegetation, soil formation, and land use in some parts of the country, while annual precipitation more strongly affects these same characteristics in other parts. Thus, in delineating boundaries, it is important to ascertain the driving properties of each ecoregion, and vary the combination of characteristics evaluated and regional management concerns considered, accordingly. If maintenance of a cold water fishery is the primary concern in one region, and reduction of soil erosion in another, the regionalization process can be customized to subdivide the ecoregions using different criteria to address their respective management issues.

The actual process of defining, delineating, describing, and depicting environmental regions can be diagrammed as a series of steps (Figure 2-1), on which the following paragraphs elaborate. The entire process centers around the decisions made during definition of the scope of the project (Figure 2-1A). The type of reference materials collected, the environmental characteristics examined for spatial patterns, the degree of detail (resolution) considered, and the specific adjustments made regarding boundary placement all depend on the resource and areal concerns and objectives defined during this initial stage. Outlining the location of areas and issues (or resources) of concern on a map assists in setting reasonable project priorities and provides a spatial layout of the logistical situations (e.g., accessibility) affecting the project. Considered in concert with desired project outputs, the map helps to clarify the level of resolution that will be needed to accomplish the project aims.

In projects designed to address more than one resource concern or objective, issues should be prioritized to set a protocol for making decisions. For instance, during consideration of transitional zones between regions, the decision of whether to divide the zone equally between the adjacent regions or include it entirely within one of the regions is based on the most meaningful outcome, given the priorities and objectives of the project. A list of priorities also helps in planning project strategies, particularly in allocation of human and monetary resources. Regional assessment strategies can be modified to cast more emphasis on specific locales, specific management practices, and specific resources.

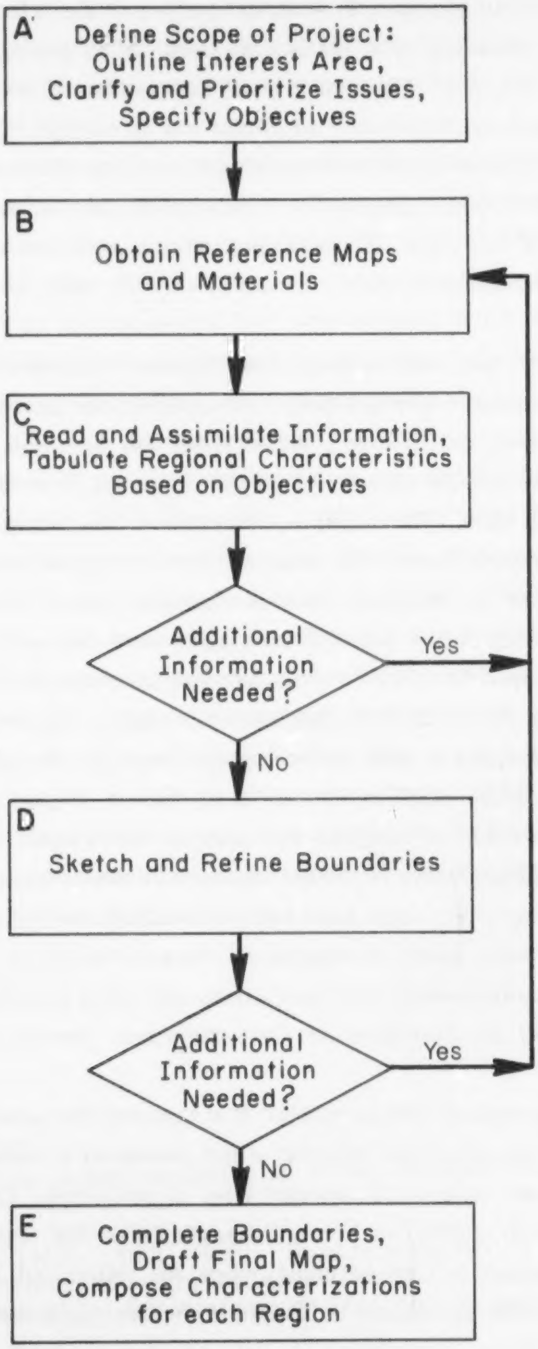
A
Define Scope of Project:
Outline Interest Area,
Clarify and Prioritize Issues,
Specify Objectives
B
Obtain Reference Maps
and Materials
C
Read and Assimilate Information,
Tabulate Regional Characteristics
Based on Objectives
Additional
Information
Needed?
Yes
No
D
Sketch and Refine Boundaries
Additional
Information
Needed?
Yes
No
E
Complete Boundaries,
Draft Final Map,
Compose Characterizations
for each Region

Figure 2-1. Flow chart illustrating the steps in regionalization. Steps A through E are explained in Section 2.3.

After issues have been prioritized, specific outputs should be clarified. The outputs may be a regional set of resource quality criteria, an analysis of the effects of a particular management practice, a regional inventory of a certain resource, or an ecologically based framework. For example, when the Arkansas Department of Pollution Control and Ecology used the ecoregion concept to classify streams, their specified output was an ecologically based framework that would (1) account for the various natural environmental conditions in the state, (2) enhance the ability to select representative reference sites for water quality testing, and (3) provide a structure for organizing analyses of site data. In specifying outputs, a decision is needed as to what level of detail will fulfill management needs. This ties directly into the resulting size of the regions delineated.

Reference maps and descriptions for regional analysis are initially sought on the environmental characteristics that are perceived to affect the issues of concern (Figure 2-1B). It is likely that additional, or different, information will be needed later in the regionalization process. The more specific the objectives, the more focused the references; some frameworks may incorporate numerical data. For example, Omernik et al. (1988) compared data for lake total phosphorus measurements along with mapped distributions of several environmental variables relating to phosphorus to delineate lake phosphorus regions for Michigan, Minnesota, and Wisconsin. Examination of the data for association with other variables, such as alkalinity and seasonal variation, helped to further refine the regional patterns in phosphorus concentrations.

After collecting reference materials and identifying the environmental factors operating within an area, we prepare a table of prospective regional characteristics based on concurrent spatial patterns of various combinations of these factors (Figure 2-1C). Additional reference information may be needed to complete this process. Sometimes, if the information has not yet been compiled and mapped, maps of related characteristics may indirectly provide the information. For instance, when vegetation maps have been unavailable, we have substituted maps of wildlife habitat classes (that were based on vegetative characteristics), or inferred plant cover using a combination of vegetation community descriptions and maps showing elevation, slope aspect, and land cover (classified as deciduous vs. non-deciduous forests and woodlands, shrubs, and grasslands).

When tabulating regional characteristics, it is apparent that some regions have a very distinct, homogeneous set of characteristics, whereas others consist of a mosaic of characteristics too small to separate into discrete units at the selected level of resolution. Occasionally, a region may not be readily divisible into subregions because changes across the region are too subtle to partition at the chosen resolution. This occurred when we delineated ecological subregions of the Southwestern Tablelands Ecoregion in Colorado, where subdivisions were perceived only by dropping down two levels in resolution (as defined from available mapped information).

When we incorporate numerical data into the regionalization process, we can include ranges of data values with the tabulation of regional characteristics. In these cases, spatial patterns of the mapped data are examined for association with terrestrial environmental characteristics. In some areas, patterns in data values will correspond well with particular features in the environment. In an analysis of the spatial distribution of lake phosphorus values, Omernik et al. (1988) noted that patterns of phosphorus values related strongly to mapped patterns of land use and potential natural vegetation in some regions, soil type in others, surficial geology in still others, and so on.

Spatial patterns of data can be extremely heterogeneous in areas characterized by a mosaic of environmental features. More detailed maps of environmental features may be needed to identify the reasons for the variability in these areas, and management expectations may need to accommodate these conditions. There may be other areas where the mapped numerical data show distinct regional patterns that do not correspond with any mapped distributions of environmental features. If the area is of comparable size to the regions being defined, it may be useful to delineate it, for the sake of management, because the values show a distinct regional pattern, even though the environmental associations are not apparent.

After completing the table of regional characteristics, we outline the regional boundaries (Figure 2-1D). Locating boundaries between some regional cores[2] may be difficult. Areas of uncertainty occur where regions abut and the landscape contains characteristics from more than one region. The decision of whether to include a transitional area within one region, or divide it among adjacent regions is based on knowledge of each region (from reference material and local experts) and consideration of how the resources of concern will be affected by regional environmental characteristics and management practices. Delineation is a necessarily subjective and evolving process; *rules* can be defined for each project, but the art of qualitative regionalization is knowing when to diverge from the rules. Additional information on environmental characteristics may be needed to support decision-making throughout the delineation process. After boundary determinations have been completed, a final map can be generated and regional descriptions can be written (Figure 2-1E).

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[2] *Regional core* refers to an area displaying all of the characteristics tabulated to define a particular region. A series of maps identifies regional cores, termed *most typical* areas, of ecoregions across the conterminous United States (Omernik 1987b, 1987c; Omernik and Gallant 1986, 1987a 1987b, 1987c, 1988). Because areas having a full set of typifying characteristics are expected to exhibit the greatest degree of within-region environmental homogeneity, they are useful for locating reference sites to measure differences among regions.

Boundaries indicating ecoregion cores do not necessarily coincide with boundaries of sub-ecoregions. Subregions are delineated from reference maps that portray more detail than those used to delineate ecoregions and cores. Features will be apparent on the more detailed maps that were not apparent on the more generalized maps. If these features are important to the subregion delineation objectives, boundary placement will be different at the two levels of regionalization.

2.4 SPECIFIC EXAMPLES OF REGIONALIZATION

2.4.1 Ecoregions of the Conterminous United States

One of our goals in developing a national ecoregion framework was to produce a map of regions that would reflect general spatial patterns in environmental resources. We did this through an analysis of a combination of maps of factors that either cause regional variations (e.g., climate, mineral availability, physiography) or integrate causal factors (soils, vegetation, land use), to distinguish distinct regional patterns of ecosystems. We used mostly small-scale, low resolution national maps and general environmental descriptions as references. The combination of small-scale maps most useful for delineating ecoregions consisted of Major Land Uses (Anderson 1970), Classes of Land-Surface Form (Hammond 1970), and Potential Natural Vegetation (Küchler 1970), along with assorted regional (multi-state) soils maps. These maps, referred to as the component maps, are discussed in further detail in the following paragraphs. Several other maps were also consulted, generally to verify the regional accuracy of each of the component maps and to provide additional details in support of the patterns that indicated ecoregions. The most helpful of these included Surficial Geology (Hunt 1979), Physical Divisions (Fenneman 1946), *Land Resource Regions and Major Land Resource Areas of the United States* (U.S. Department of Agricultural 1981), maps in *Climates of the United States* (Baldwin 1973), and Census of Agriculture Graphic Summaries (U.S. Department of Commerce, Bureau of the Census 1969, 1973, 1978, 1982).

One of the major controversies concerning the delineation of environmental regions has centered around analyzing patterns of land use in addition to patterns of natural features. In one of the earliest efforts to define ecological regions, Herbertson (1905) examined the distributions of a combination of natural factors (land-surface form, climate, and vegetation) along with distribution of human development. Neither his belief that human development should be considered, nor his notion of summarizing a combination of factors to define regions were well received. The concept that land use patterns might reflect land potential, and therefore be useful for defining regions, later became even less acceptable. It was thought by some that this was to subscribe to *environmental determinism*[3]. Others felt that only factors relating to natural processes should be examined, rather than surrogates reflecting natural conditions, regardless of how close the connection. Today, these beliefs are less prevalent, and the use of any sources that aid in the definition of regions is more permissible. Recent evidence of wider acceptance is found in

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[3] Environmental determinism refers to the concept that physical characteristics in the environment, such as climate and soil type, control the distribution and nature of human occupation. The counter-view is that human distribution is more dependent upon cultural, rather than physical, dictates, because humans can modify their habits and technology in order to overcome environmental influences. These competing paradigms have been strongly debated by geographers throughout much of the twentieth century.

Robinson et al. (1978, section on dasymetric mapping) and Wiken (1986, explanation of Terrestrial Ecozones of Canada).

Our purpose for employing maps of land use is several-fold. First, it is not our intention to define regions because of their land use, but rather to use land use maps as an indication of where spatial changes in natural environmental characteristics, and therefore in resource quality, occur. The ability of an area to support and withstand a particular economy largely results from a particular aggregation of environmental characteristics. Land use can be considered an integrator of features such as climate, mineral availability and substrate, presence and quality of surface and subsurface water, physiography, natural vegetation, and so on. As these features change from place to place, so does the total capacity of the land to support a specific land use. Land use maps indicate where these spatial changes occur--where forestry resources, for instance, dwindle and rangeland economy is more aptly supported. Land use maps indicate areas where water resources support irrigated rather than dryland farm agriculture, or where subtle environmental changes favor raising cattle rather than sheep. The environmental variations responsible for these changes can be observed on some or all of the component maps, but without a land use map to serve as an indicator of change, many of the nuances pointing to prospective regions might be overlooked.

Second, land use maps indicate the spatial patterns of management practices likely to affect the regional quality of resources. Management expectations for areas subjected to generations of a particular type of land use cannot reasonably be based on pristine conditions. In many areas, present land cover is so altered from original vegetation cover that plant litter contributions to water chemistry are vastly different from what would be expected from studying only maps of potential natural vegetation, climate, physiography, and soils. Our experiences in determining relationships between nonpoint sources and stream nutrient levels (Omernik 1977), defining patterns of sensitivity of surface waters to acidification, and refining maps of regional patterns of lake trophic state have demonstrated that land use patterns correspond well with spatial patterns of aquatic resource quality. Maps depicting patterns of geology and soils, although also used in our assessments, have never corresponded as well with these variables.

Finally, land use maps are generally more accurate than the other component maps. Like physiography, land use can be seen and, thus, mapped more accurately than factors that must be interpolated (e.g., geology, soils, and potential natural vegetation) based on data that may or may not be representative. Furthermore, land use is mapped at a finer resolution. It is compiled from more detailed and complete data than the other maps, often from complete aerial imagery coverage and ground-truthing. However, it is always important to use land use maps in conjunction with maps of the other environmental factors because the spread of urbanization and advances in modern agricultural technology can override natural regional potential.

Like a land use map, a map of potential natural vegetation is a strong integrative tool for illustrating ecosystem patterns. Potential natural vegetation was defined by Küchler (1970) as the vegetation that would exist today if man were removed from the scene and if the resulting plant succession were telescoped into a single moment. Küchler used a variety of sources, mostly maps, of varying accuracy, scale, and level of generality to infer the vegetation communities that would exist in the absence of human modification. Because Küchler did not have access to an extensive, quality controlled data base, the map is less accurate, and the accuracy and level of detail less consistent across the country than the land use map.

Regional patterns of slope, local relief, and profile type (e.g., how much of the more gently sloping land is located near the larger streams, or away in the interfluves) have been synthesized into relatively homogeneous classes of land-surface form by Hammond (1970). The map was compiled at a coarser level of resolution than either the land use or the potential natural vegetation map.

We were not able to locate a national soils map with an acceptable degree of accuracy and consistency. The classification scheme of the soil taxonomy map developed by the U.S. Department of Agriculture, Soil Conservation Service (1970) appeared to be most appropriate for our purposes, but we found much disagreement between the units classified on this map and those shown on regional and state soils maps. Gersmehl (1977) reported that the inaccuracies shown on the USDA, Soil Conservation Service map resulted largely from poor base data and inappropriate compilation techniques. Thus, we relied mainly on regional- and state-level soils maps for assessing regional patterns.

Because of the interrelatedness of the environmental factors depicted on these component maps, and on the other reference maps we analyzed (e.g., Baldwin 1973; Fenneman 1946; Hunt 1979; U.S. Department of Commerce, Bureau of the Census 1969, 1973, 1978; U.S. Department of Agriculture 1981), we expected congruent spatial patterns across maps of different variables. The four main component maps were analyzed together to detect potential regions that were relatively homogeneous in overlapping patterns of soils, land use, land-surface form, and potential natural vegetation. The identifying classes of each component were tabulated to characterize each prospective ecoregion. The key to this process was distinguishing the overall regional homogeneity in a combination of characteristics from the heterogeneity in each characteristic. Some ecoregions could be clearly and easily delineated because of the distinctiveness of all four characteristics relative to adjacent ecoregions; other regions were less distinct and were distinguished by broader classes or groupings of some of the characteristics.

The size of each ecoregion was a function of within-region homogeneity relative to among-region variation at a spatial scale believed to be most useful for state and regional resource management. For these purposes, ecoregions could not be so large as to contain entire topographic watersheds greater than 500 km^2 that exhibited characteristics more indicative of other, contrasting areas or regions. This resulted in a range of ecoregion sizes, from 15,000 km^2 (i.e., the Willamette Valley Ecoregion) to 330,000 km^2 (i.e., the Southeastern Plains Ecoregion), but commonly on the order of 130,000 km^2. Some regions exhibited a mosaic of conditions common throughout the region, that were too small and patchy to allow further delineation at this resolution. The Central Appalachian Ridge and Valley Ecoregion, for example, was characterized by such contrasts; there, drainage basins of at least 500 km^2 all contain forested mountains and agricultural valley bottoms.

Delineating actual regional boundaries involved an iterative process of both map overlay and qualitative analysis of the relative accuracy and level of generality of each component map. Potential regions were initially sketched and typifying characteristics were tabulated. Boundaries were located using those component maps determined to be most relevant for defining each region. Since each component map was compiled at a different level of generality, with varying levels of accuracy relative to the true locations of the characteristics represented, as well as to the source material used in map compilation, the usefulness of the map alignments for drawing ecoregion boundaries varied. After superimposing the component maps, evaluating and compensating for the differences in accuracies and generalities of each, and identifying the obvious regional interrelationships among the component characteristics, final ecoregion boundaries were drawn. An example of the component map alignments used in the delineation of the Nebraska Sand Hills Ecoregion is shown in Figure 2-2. Examples of the decisions and rationale used in regionalization are presented in further detail in the following subsection.

The component maps in Figure 2-2 all show the same regional pattern for the Sand Hills area, but boundary placement varies from map to map. In this case, the final ecoregion boundary was derived by overlaying and mentally averaging the boundaries from the four component maps (in other cases, the importance of boundaries on individual component maps was weighted differently, due to knowledge about map quality or detail). In averaging these boundaries, we *smoothed* the more detailed resolution portrayed on the land use and potential natural vegetation maps to depict the general nature of our ecoregion framework at a map scale of 1:7,500,000.

In actuality, there is no discrete, correct location for placement of lines on a map, because regional boundaries represent transitional areas. Sites located near regional boundaries often have characteristics typical of more than one region. For this reason, it is necessary to field-check specific sites to judge which region the site environmental characteristics most nearly represent. The environmental characteristics used to define each ecoregion in the conterminous United States appear in tables printed on the back of national and regional ecoregion maps (Omernik 1987a, 1987b, 1987c; Omernik and Gallant 1987a, 1987b, 1987c, 1988).

For final depiction, the ecoregions were color-coded to convey a sense of broader, multi-regional patterns. This was done by selecting colors that conveyed common perceptions reflecting vegetative cover and/or land use. Regions characterized mostly by cropland were assigned shades of orange and brown. Regions characterized by forests were assigned shades of green; and regions characterized by wetlands or very wet forests were assigned shades of blue. Grasslands were generally depicted by shades of yellow, and very arid areas by shades of pink or red. Regions characterized by a mosaic of vegetative cover or land use were generally assigned a color midway between those usually used to portray the individual characteristics. Because of the proximity of similar regions in parts of the country, it was sometimes necessary to assign a color merely to contrast with the surrounding hues.

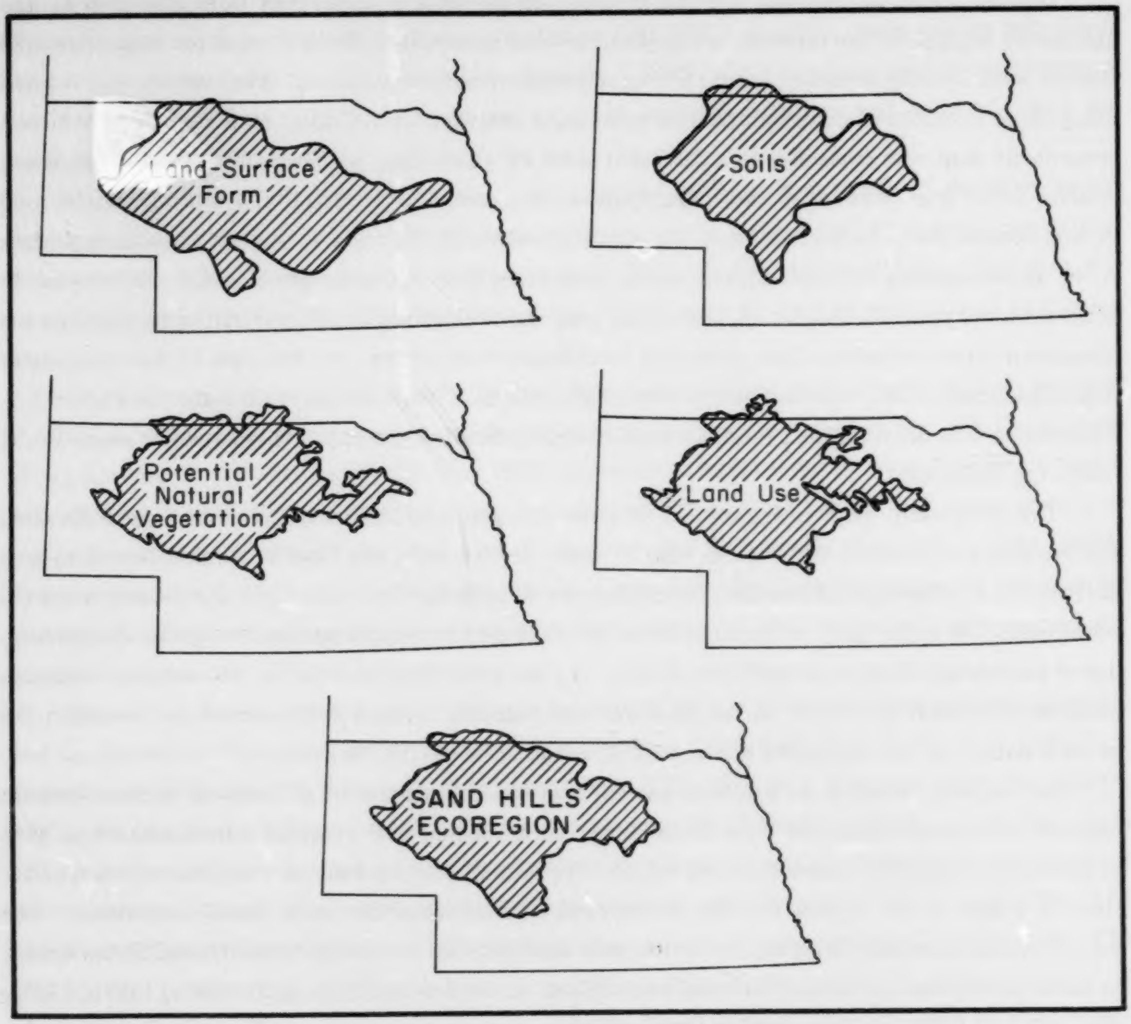
Land-Surface Form
Soils
Potential Natural Vegetation
Land Use
SAND HILLS ECOREGION

Figure 2-2. Spatial distributions of four environmental characteristics used to delineate the Sand Hills Ecoregion. The general agreement of patterns in land-surface form (Hammond 1970), soils (U.S. Department of Agriculture, Soil Conservation Service 1970), potential natural vegetation (Küchler 1970), and land use (Anderson 1970) clearly suggests a distinct area. Differences in the relative accuracy and resolution of information shown on maps of these characteristics necessitated qualitative analysis of these and other maps of the area to determine the actual limits of the combination of factors that identify the regions.

We have since aggregated ecoregions to address broader areas of interest at national levels of management (these maps exist in draft form only). For example, concerns of the Environmental Protection Agency resulted in the delineation of four different aggregate frameworks to address surface water ecosystems, agricultural ecosystems, forest ecosystems, and wetlands ecosystems. The aggregation of ecoregions is somewhat different for each category of ecosystem because of the different priorities and interests in each of the four subject areas. Ecoregions have also been subdivided to sort within-region variability to increase management utility at the state level. An example of the latter is detailed in the following subsection.

2.4.2. Ecological Subregions of Colorado

Because of interest shown by the Environmental Protection Agency regional office in Denver, Colorado, we designed a higher resolution ecoregion map for inventory, monitoring, and assessment of surface water resources in Colorado. The framework was based on sorting within-region variability of ecoregions delineated by Omernik (1987a) and Omernik and Gallant (1987a), resulting in ecological subdivisions of ecoregions (Plate 1). The resulting map units were more consistent in size with areas investigated and reported on by the state. Subregion size was generally dictated by concurrent distributional patterns of most environmental features shown on 1:500,000-scale to 1:2,000,000-scale reference maps.

To subdivide individual ecoregions, we gathered maps and other interpretive references on a variety of environmental characteristics for Colorado and the surrounding states (Appendix A). Since ecoregion boundaries and resource management responsibilities transcend state boundaries, we obtained reference maps for states outside of Colorado to cover the extent of the ecoregions. This enabled us to understand how environmental patterns occurring in Colorado fit within the larger ecoregion context. We then appraised the suitability and quality of the reference materials and began a second information search to strengthen the more questionable references.

We used the same process as previously described for defining and delineating *Ecoregions of the Conterminous United States* (Subsection 2.4.1), but at a finer resolution. Our intent throughout Subsections 2.4.2.1 to 2.4.2.12 is to provide examples that document regionalization, including how we perceive regions and subregions, how we decide on the most important characteristics for distinguishing regions and subregions, and how we decide to segregate an area as a subregion at a particular level of resolution. The numerical designations following the name of each ecoregion are based on map unit numbers published on national (Omernik 1987a) and multi-state (Omernik and Gallant 1987a) ecoregion maps.

2.4.2.1 Description of the Wyoming Basin Ecoregion (map unit #18)--

Most of the Wyoming Basin Ecoregion receives less than 300 mm of precipitation annually. The level to irregular terrain is broken by steep-sided drainage channels and occasional hills and low mountains. High mountains border the Basin, supplying the primary perennial streamflow to the ecoregion. The ecoregion is dominated by arid shrublands. Big sagebrush is the dominant shrub in many areas, intermixed with rhizomatous wheatgrasses, drought resistant bluegrass species, needle-and-thread, Indian ricegrass, bitterbrush, balsamroot, and lupine. Saltdeserts are sparsely inhabited by saltbush, greasewood, iodinebush, sagewort, saltgrass, winterfat, and hopsage. There are some woodland communities, characterized by Rocky Mountain juniper and oak scrub. Ustic Torriorthents are the dominant soils. The region as a whole is used for rangeland, but many areas lack sufficient vegetation to support livestock.

2.4.2.2 Subregionalization of the Wyoming Basin Ecoregion--

In assessing which environmental characteristics would most affect aquatic resource quality in this ecoregion, we noticed that the greatest degree of environmental variability was depicted on the vegetation map. However, at the resolution of our reference maps, none of the other environmental characteristics showed patterns concurrent with those on the vegetation map. The vegetation map indicated that saltdesert vegetation communities throughout Colorado and surrounding states generally colonize the most arid areas. In the Wyoming Basin Ecoregion, however, sagebrush communities, usually found in relatively less arid areas than saltdesert communities, occur in the driest tracts. We felt that in both plant community types, grazing and recreation potential would be very low, surface erosion would be high, and most of the drainages would be intermittent or ephemeral, so there was little reason for partitioning subregions based on the two plant community types.

On examination of woodland communities, we found that they inhabit either steep sidewalls of tablelands and dry (throughout most of the year) drainages in the arid portions of the ecoregion, or slopes of high hills and low mountains in the semiarid portions. In the first case, areas would be subject to a high degree of alluvial and colluvial erosion and, because of inaccessibility due to steepness of terrain, would offer extremely low potential for recreation and grazing. Such areas would have somewhat lower water quality potential because higher rates of erosion would result in higher stream sediment loads as compared to the lower relief shrublands; but, as the shrublands themselves offer very limited potential, there is no strong reason to distinguish this type of wooded area separately. In the case of the other type of woodland habitat, rainfall and runoff conditions offer somewhat better water quality potential than the regional norm, averaging from 300 to 400 mm of rainfall and 25 to 50 mm of runoff each year. These woodlands inhabit isolated hills and mountains, and offer relatively better quality resources for recreation and grazing. Nevertheless, their areal extent is so small in Colorado (they are more extensive in Wyoming), that they are not clearly represented on our reference maps. This type of detail would be suitable for delineation at a still finer resolution, but not at the level of our maps.

Examination of the Wyoming Basin Ecoregion resulted in recognition of one subregion within the Colorado portion of the ecoregion (subregion numbers correspond with those depicted on the map of Ecological Subregions of Colorado [Plate 1]):

a. Semiarid to arid shrublands of the Wyoming Basin (map unit #18-1)

1. **Climate** - Arid to semiarid. Much of the subregion receives less than 300 mm of precipitation annually; the rest receives between 300 and 400 mm. The Wyoming portion is drier, averaging only 175 mm in some areas. Precipitation occurs mainly in spring and fall.

2. **Physiography** - Irregular basin terrain with isolated mountains and plateaus. Local relief (i.e., the variation in topographic relief over 10 km^2) is generally greater than 30 m, and often greater than 120 m. Steep side slopes of uplands can have 180 m of local relief.

3. **Land Use** - Extremely low capacity rangeland for beef cattle and sheep.

4. **Vegetation** - Widely scattered shrubs. Sagebrush-dominated shrublands include big sagebrush mixed with drought resistant grasses such as wheatgrass, fescue, and bluegrass species, needle-and-thread, and Indian ricegrass. Saltbush-dominated shrublands include saltbush, greasewood, iodinebush, sagewort, saltgrass, winterfat, and hopsage. Rocky Mountain juniper and piñon pine are found on some uplands.

5. **Soils** - Entisols[4].

6. **Relative Surface Water Quality** - Surface water resources are mainly intermittent and ephemeral streams. The few perennial streams originate from the surrounding mountainous ecoregions. The sparse rural population relies heavily upon the meager subsurface water supply. Surface water quality is affected by input from highly erodible soils (some soils have naturally high salinity and alkalinity), amplified by high evaporation rates and water withdrawals.

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[4] Maps depicting soil types were not useful for sorting the within-region variability of most of the ecoregions in Colorado. Thus, soil information usually reflects the resolution perceived at the ecoregion, rather than subregion, level.

2.4.2.3 Description of the Colorado Plateaus Ecoregion (#20)--

Rugged tableland topography is typical of the Colorado Plateaus Ecoregion. Precipitous side-walls mark abrupt changes in local relief, often from 300 to 600 m. The regional climate is arid to semi-arid, with most of the region receiving less than 400 mm of precipitation annually, although a few areas receive 500 or 600 mm. Low annual rainfall and high rates of evaporation render nearly all of the regional surface waters intermittent or ephemeral; perennial streams have headwaters in the adjacent Southern Rockies Ecoregion. The Colorado Plateaus are used mainly as rangeland, although the naturally sparse vegetation does not support much livestock. Soils are mostly Entisols and Aridisols. Vegetation is similar to that of the Wyoming Basin Ecoregion; shrublands are dominated by big sagebrush or saltbush-greasewood; piñon-juniper woodlands occur on uplands to a much greater extent than in the Wyoming Basin.

2.4.2.4 Subregionalization of the Colorado Plateaus Ecoregion--

Reference maps and text for the Colorado Plateaus Ecoregion indicate that high salinity in soils and surface and subsurface waters affect vegetation and, consequently, land use capability in several areas within the ecoregion, although distribution patterns on the soils map did not correspond with these patterns. Saline areas are generally associated with lower rangeland potential than nonsaline areas, average annual precipitation of less than 250 mm per year, and deposits of Mancos shale (the weathering of this particular formation is known to be associated with high salinity in soil and water). All of these factors reinforced the need for separating the saltdeserts from the remainder of the ecoregion.

Another association occurs between areas of greater topographic relief and areas populated by woodland vegetation. Juniper and piñon often occupy steep, rocky terrain, which is less accessible to livestock and more susceptible to erosion. Thus, rangeland potential is ultimately lower in wooded than nonwooded areas, although for flatter, drier tracts having little or no vegetation, woodland grazing capacity may be greater[5]. We felt it worthwhile to separate wooded areas from shrubland dominated areas, resulting in the delineation of three subregions:

a. Desert Shrublands of the Colorado Plateaus Ecoregion (map unit #20-1)

1. **Climate** - Arid to semiarid. 200 to 400 mm precipitation over most of subregion; a few areas receive up to 500 mm. High rates of evaporation.

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[5] There is some degree of overlap of resource quality in all subregions in the Colorado Plateaus Ecoregion because of the variability in environmental characteristics. This is probably true of subregions in most ecoregions.

2. **Physiography** - Irregular plains to tablelands, where local relief commonly is between 200 to 300 m.

3. **Land Use** - Rangeland. Of the three subregions, this one generally has the best grazing potential, but range quality is still very low.

4. **Vegetation** - Sagebrush shrubland; mainly includes big sagebrush, rabbitbrush, and assorted drought-resistant grasses (e.g., wheatgrass, Indian ricegrass, bluegrass).

5. **Soils** - Aridisols and Entisols.

6. **Relative Surface Water Quality** - Surface water resources exist mainly as intermittent and ephemeral streams. Perennial streams originate in neighboring mountainous ecoregions. Stream quality is affected by high concentrations of sediments and salinity from highly erodible soils.

b. Saltdeserts of the Colorado Plateaus Ecoregion (map unit #20-2)

1. **Climate** - Arid. Less than 250 mm precipitation annually, mostly occurring in fall and spring.

2. **Physiography** - Nearly level to irregular valley floors.

3. **Land Use** - Mostly poor quality rangeland for beef cattle and sheep. Irrigated agriculture is concentrated in river valleys where perennial streams flow from neighboring mountainous ecoregions. Orchard crops (apples, peaches, pears, cherries), hay, grain, and vegetables (e.g., onions, beans) are cultivated in these valleys.

4. **Vegetation** - Saltbush shrubland; includes saltbush, greasewood, rabbitbrush, horsebrush, and grasses (Indian ricegrass, galleta).

5. **Soils** - Aridisols and Entisols.

6. **Relative Surface Water Quality** - Surface water primarily occurs as intermittent and ephemeral streams. Perennial flow is sustained in streams originating from neighboring mountainous ecoregions. Stream quality is affected by highly erodible soils, naturally high salinity (magnified by irrigation return flows from cropland), runoff of farm chemicals, and municipal wastes.

c. Wooded Uplands of the Colorado Plateaus Ecoregion (map unit #20-3)

1. **Climate** - Arid to semiarid. 200 to 400 mm precipitation occurs annually over most of subregion; greater than 600 mm occurs around Douglas Pass in Garfield County, CO.

2. **Physiography** - Tablelands; local relief is often from 200 to 300 m.

3. **Land Use** - Very poor quality rangeland for beef cattle and sheep. Of the three subregions, this one generally offers the lowest grazing potential. It has the rockiest terrain, is typically farthest from surface water supply, and has the lowest density of suitable forage.

4. **Vegetation** - Juniper and piñon pine woodland. Grass and shrub understory includes wheatgrass, Indian ricegrass, grama, and sagebrush.

5. **Soils** - Aridisols and Entisols.

6. **Relative Surface Water Quality** - Surface water supplies are intermittent and ephemeral. Rare locations include portions of perennial streams flowing from adjacent mountainous ecoregions. Water quality is affected by low annual precipitation, high rates of evaporation, highly erodible soils, and naturally high salinity.

2.4.2.5 Description of the Southern Rockies Ecoregion (#21)--

The Southern Rockies Ecoregion has the most distinct set of environmental characteristics of all of the Colorado ecoregions. The region is dominated by high elevation, steep, rugged mountains; coniferous forests cover much of the ecoregion. The range of average annual precipitation is very large, from less than 300 mm to more than 1,500 mm. Precipitation occurs both as snow and rain and supports primarily perennial surface waters.

Mountains of 3,300 to 3,600 m above sea level are common, although many are higher. At these elevations, vegetation is limited to low growth shrubs, cushion plants, and forbs. Stunted, deformed conifers mark the upper tree-line at about 3,350 m. Below this, cool, moist habitats, blanketed by snow much of the year, are inhabited by spruce-fir forests. Middle and lower elevations (down to 1,700 m) provide warm, dry habitats colonized by both evergreen and deciduous trees, while large semiarid to arid pockets are populated by shrubland species. Soils throughout the mountains have formed from a variety of sedimentary and crystalline materials. The distribution of major soil orders follows a pattern of elevational banding, much like that found in the distribution of major vegetation types.

Recreation, livestock grazing, wildlife habitat, and mining are the leading land uses in the Southern Rockies. Recreation occurs at all elevations and includes year-round outdoor sports. Livestock graze areas that are snow-free three or more months of the year. A variety of metals and other elements are mined throughout the ecoregion; two areas of particularly intensive mining occur in the mountains west and southwest of Denver, near Leadville and Breckenridge, and in the southwestern portion of the state, around Telluride, Silverton, and Ouray.

2.4.2.6 Subregionalization of the Southern Rockies Ecoregion--

The correspondence between distribution patterns of climate, soil development, vegetation, and land use with elevation is an outstanding feature of the Southern Rockies Ecoregion. Other factors, such as slope aspect, degree of topographic relief, and surficial geology, also affect these distributions, but on a more local level.

Information from the reference maps and texts indicated a number of potential subregions. Our main aim was to produce a framework that would recognize only the most important ones, without becoming distracted by details. We were concerned with recognizing too many subregion types, because the convoluted nature of the Rocky Mountains, combined with the climatic elevational gradient, could lead to delineation of numerous discontinuous areas too small to reasonably monitor and manage. Also, too many subregion classes would hinder the extrapolation of information at this level of resolution. These details would be more properly recognized at a finer scale, using more detailed component maps to sort variability.

Certain prospective subregions are more obvious than others. One of these is the high alpine, rugged terrain dominated by glacial meltwaters, exposed rock, young soils, sparse krummholz trees, and periglacial vegetation. This area, covered with snow nearly year-round, is relatively free of impact from land development, livestock grazing, and mineral extraction. Another conspicuous subregion class is the low to mid-elevation, arid to semiarid area vegetated by scrub trees, shrubs, and grasses, and subject to land development and heavy impact from grazing. More difficult to resolve is the band of relatively ungrazed, varied coniferous forests separating these two subregion classes.

We decided to split the forested middle ground into (1) a higher elevation zone, covered predominantly by spruce-fir forests, and (2) a lower elevation zone, colonized by a patchwork of forest types including blue spruce, Douglas-fir, white fir, and ponderosa pine. Our intent was to separate the areas likely to produce higher water quality (less hospitable to biota, less biomass input from plants and animals, and less human impact), from those likely to produce relatively lower water quality (more accessible, more input from forest understory, and more land development and grazing).

We used ecosystem descriptions and maps depicting land use/land cover, topographic contours, and annual precipitation to help us determine the boundary between what we believed were the two qualitatively different subregions. In general, spruce-fir forests are associated with the higher quality areas. Certain species, such as aspen and Gambel oak, are ubiquitous throughout the coniferous zones. The four subregions delineated for the Southern Rockies Ecoregion consist of:

a. High Elevation Tundra of the Southern Rockies Ecoregion (map unit #21-1)

1. **Climate** - Cold and humid to arid. Although annual precipitation is from 750 to 1,500 mm, mostly occurring as snow, snow is removed by strong winds in some areas, resulting in locally arid environments.

2. **Physiography** - Mountaintops above 3,300 m. Local relief is from 300 to 600 m.

3. **Land Use** - Wildlife habitat and recreation. Use is limited by inaccessibility, as most portions are snow-free for only four to six weeks. Some portions are perennially snow-covered.

4. **Vegetation** - Periglacial vegetation of low growth shrubs, cushion plants, and forbs. The forest-tundra interface (around 3,300 to 3,600 m elevation) is sparsely colonized by stunted, deformed Englemann spruce, subalpine fir, limber pine, and bristlecone pine.

5. **Soils** - Pergelic Cryumbrepts and Cryochrepts, formed largely from crystalline rocks and rock outcrops.

6. **Relative Surface Water Quality** - Surface water is plentiful, consisting of perennial streams and small lakes. High quality is maintained due to inaccessibility to humans and large mammals throughout most of the year.

b. Cool and Moist Forests of the Middle to High Elevations of the Southern Rockies Ecoregion (map unit #21-2)

1. **Climate** - Cool and humid. 750 to 1,000 mm of annual precipitation falls over most of the subregion, mainly as snow, and remains on the ground well into the summer months.

2. **Physiography** - Steep slopes of the Rocky Mountains, from about 2,700 to 3,300 m elevation. Local relief is often from 300 to 600 m or more.

3. **Land Use** - Wildlife habitat, recreation, and mining. Grazing is limited by climatic conditions, lack of forage vegetation, and inaccessibility from excessively steep terrain and lingering snowpack.

4. **Vegetation** - Dense forests dominated by Engelmann spruce and subalpine fir; some areas are locally dominated by aspen. Forest understory is sparse.

5. **Soils** - Rock outcrops and Cryoboralfs and Haploborolls weathered from a variety of crystalline and sedimentary materials.

6. **Relative Surface Water Quality** - Abundant perennial streams and small lakes have fairly high quality except where disturbed by mining activities.

c. Warm and Dry Forests of the Middle to Low Elevations of the Southern Rockies Ecoregion (map unit #21-3)

1. **Climate** - Warm and dry. Average annual precipitation is about 400 to 750 mm, occurring as both snow and rain. The annual snow-free period lasts a minimum of four months.

2. **Physiography** - Steep, lower to mid-elevation mountain slopes of the Southern Rockies (about 1,700 to 2,700 m). Local relief is from 300 to 400 m.

3. **Land Use** - Livestock grazing, wildlife habitat, mineral extraction and recreation.

4. **Vegetation** - Variety of communities including aspen, Douglas-fir, ponderosa pine, Gambel oak, and piñon pine-juniper woodlands.

5. **Soils** - Borolls and Boralfs. Derived from crystalline and sedimentary rocks under various conditions ranging from cold, humid, high elevation forests to warm, semiarid, low elevation shrublands and grasslands.

6. **Relative Surface Water Quality** - Surface water occurs mainly as perennial streams. Resources are plentiful, and are affected mainly by livestock grazing and trampling of riparian vegetation, mineral extraction, particularly placer mining, and recreational and rural developments.

d. Low to Middle Elevation, Semi-Desert Shrublands of the Southern Rockies Ecoregion (map unit #21-4)

1. **Climate** - Semiarid. Receives from 300 to 400 mm of annual precipitation, mainly as rain.

2. **Physiography** - Rolling to irregular terrain of the lower to mid-elevation portions of the Southern Rockies. Local relief varies from 60 to 300 m.

3. **Land Use** - Grazing. Areas adjacent to large perennial streams are irrigated.

4. **Vegetation** - Shrublands of greasewood, four-winged saltbush, shadscale, and sagebrush, often interspersed with grasses.

5. **Soils** - Borolls. Derived from a variety of sedimentary and crystalline rocks.

6. **Relative Surface Water Quality** - Water resources occur mainly as perennial and intermittent streams. Quality is poor, affected by grazing, mineral extraction and, along some streams, rural community wastes and farm chemicals.

2.4.2.7 Description of the Arizona/New Mexico Plateau Ecoregion (#22)--

The Arizona/New Mexico Plateau Ecoregion represents a large transitional region between the semiarid grasslands and low relief tablelands of the Southwestern Tablelands Ecoregion and the drier woodlands and shrubs and higher relief tablelands of the Colorado Plateaus Ecoregion. Comprising the *gradient* between these two ecoregions, the Arizona/New Mexico Plateau has shrublands of big sagebrush, rabbitbrush, and winterfat, woodlands of piñon pine and juniper, and grasslands of western wheatgrass, green needlegrass, blue grama, and needle-and-thread. Local relief varies from a few meters, on plains and mesa tops, to well over 300 m along tableland side slopes. The ecoregion has a semiarid to arid climate, receiving between 300 and 400 mm of precipitation annually.

Rangeland is the primary land use throughout most of the ecoregion; but a large and contrastingly unique area in Colorado, the San Luis Valley, is a nearly isolated, relatively flat, arid (less than 200 mm precipitation annually) valley, with enough perennial stream flow and groundwater from the surrounding Southern Rocky Mountains to support irrigated agriculture. Other cropland areas within the ecoregion are very small, widely scattered tracts along large perennial streams. Other than perennial stream flow originating in nearby mountainous regions, surface water resources in this ecoregion consist of intermittent and ephemeral streams.

2.4.2.8 Subregionalization of the Arizona/New Mexico Plateau Ecoregion--

Ecosystems are similar to those found in the Southwestern Tablelands and Colorado Plateaus Ecoregions. The driest areas (200 mm of annual precipitation or less) coincide with relatively flat to irregular plains supporting a saltbush-greasewood shrub community. Big sagebrush communities are common elsewhere throughout the ecoregion. Grasses cover large areas, generally providing better range conditions than are found in shrublands. In the few areas where perennial streamflow is available and terrain is relatively flat, land is irrigated for crops.

We perceived a difference in aquatic resource potential for the most arid portions of the region. This resulted in delineation of a saltdesert subregion. We were not able to explain the distribution patterns in grassland and shrubland communities using reference maps at this level of resolution, so these were grouped into one subregion. We also had trouble understanding the distribution of land use patterns within the ecoregion. In the San Luis Valley, larger tracts of irrigated acreage occur adjacent to nonirrigated acreage, but we saw nothing on the rest of the reference maps to explain the change in economic resource potential. Because of the likely effects of irrigation on surface and subsurface water quality over such a large area, we needed to investigate related environmental factors on a finer scale of resolution to understand the distribution of the different land uses.

At a finer level of detail, it became evident that only the flattest areas are cultivated; cropping stops when a certain degree of surface irregularity is encountered. This information is evident from 1:250,000-scale land use and topographic maps but not from the smaller scale, 1:500,000 to 1:2,000,000 maps used for the rest of the regional assessment. Although our intention was to delineate regional subdivisions based on mid-scale resolution, we felt the need to identify the irrigated cropland area as a separate subregion because of the relatively extensive and intensive effects on water quality resources. In this case, we purposely deviated from our initial *rules* by examining maps of a larger scale than those used for other subregions. We delineated other, smaller irrigated cropland areas throughout the ecoregion in order to be consistent with this subregion class. Our interpretation of characteristics in the Arizona/New Mexico Plateau Ecoregion led to the classification of three subregions:

a. Shrublands of the Arizona/New Mexico Plateau Ecoregion (map unit #22-1)

1. **Climate** - Semiarid. 230 to 450 mm of precipitation received annually.

2. **Physiography** - Irregular plains, moderate to high relief plateaus, and open, low mountains. Local relief varies from 30 m on irregular plains, to 300 m or more near high tablelands.

3. **Land Use** - Low density livestock grazing mostly for beef cattle and sheep.

4. **Vegetation** - Communities range from shrublands of big sagebrush, rabbitbrush, and winterfat to grasslands of western wheatgrass, green needlegrass, blue grama, and needle-and-thread.

5. **Soils** - Mostly Argids, also Psammaquents and Orthents.

6. **Relative Surface Water Quality** - Surface water resources consist mostly of intermittent and ephemeral streams. A few perennial streams flow from the nearby Southern Rockies. Streams are impacted by highly erodible sediments.

b. Irrigated Flatlands of the Arizona/New Mexico Plateau Ecoregion (map unit #22-2)

1. **Climate** - Arid. Receives 200 mm or less of annual precipitation.

2. **Physiography** - Flat to low relief plains. Local relief is a few meters or less.

3. **Land Use** - Irrigated agriculture. Main crops include barley, malt, alfalfa, small grains, hay, Irish potatoes, and a few other assorted vegetables.

4. **Vegetation** - Original shrublands were dominated by shadscale saltbush and greasewood. Natural vegetation has been removed for cropland acreage.

5. **Soils** - Mostly Argids, also Psammaquents and Orthents.

6. **Relative Surface Water Quality** - Surface water resources consist mostly of intermittent and ephemeral streams. Perennial flow occurs in a few large streams derived from the nearby Southern Rockies. Streams are impacted by highly erodible sediments, water withdrawal, high salinity, especially from irrigation return flow, and runoff of farm chemicals in areas of irrigated agriculture.

c. Saltdeserts of the Arizona/New Mexico Plateau Ecoregion (map unit #22-3)

1. **Climate** - Arid. Less than 250 mm annual precipitation.

2. **Physiography** - Irregular plains of low to moderate relief. Local relief varies accordingly, from several meters to 60 m.

3. **Land Use** - Low to very low density livestock grazing, mostly for beef cattle and sheep.

4. **Vegetation** - Shrublands dominated by shadscale saltbush and greasewood. Sagebrush, horsebrush, spiny hopsage, rabbitbrush, saltgrass, and alkali sacaton also occur.

5. **Soils** - Mostly Argids, also Psammaquents and Orthents.

6. **Relative Surface Water Quality** - Surface water resources consist mostly of intermittent and ephemeral streams. A few perennial streams flow from the nearby Southern Rockies. Streams are impacted by highly erodible sediments and high salinity.

2.4.2.9 Description of the Western High Plains Ecoregion (#25)--

The bulk of Colorado's cropland is in the Western High Plains Ecoregion. Large tracts of land are dry-farmed or irrigated for corn, wheat, sorghum, alfalfa, beans, sugar beets, onions, and a small variety of other vegetables. The semiarid climate supports grassland communities, providing range for beef cattle and sheep. Swine and poultry are also raised. Population centers occur along the foothills of the Rockies, on the western edge of the region, and along the South Platte River.

Most of the region consists of smooth to irregular plains; local relief varies from a few meters to 30 m. Soils have been formed from sedimentary materials and are predominantly Mollisols, although large areas of Entisols and Aridisols are distributed throughout the ecoregion. Three hundred to 400 mm of precipitation falls annually, mainly during late spring through early fall. Surface waters are mostly intermittent and ephemeral streams. Perennial streams, such as the Arkansas and the Platte, originate in the Southern Rockies Ecoregion. Where available, groundwater supplies are used for stock watering ponds and irrigation.

2.4.2.10 Subregionalization of the Western High Plains Ecoregion--

Reference maps indicate that subregional patterns in this ecoregion are primarily linked to local topography and type of surface deposit. Flat to gradual plains are cultivated, while areas of greater surface irregularity are used as range. Sandy loessal deposits consistently correspond with patterns of poorly developed soils, sandhills grasses, and livestock grazing. Regardless of terrestrial characteristics, locales having available surface or subsurface water supplies and minimal topographic relief are irrigated for crops. Thus, irrigated agriculture is not indicative of particular climatic condition, substrate, vegetation, or soil type; it is superimposed over these characteristics whenever water is available. Based on these observations, we delineated three subregions:

a. Rolling Sand Plains of the Western High Plains Ecoregion (map unit #25-1)

1. **Climate** - Semiarid. 200 to 300 mm of precipitation received annually.
2. **Physiography** - Sandy rolling plains. Local relief is often around 15 m.
3. **Land Use** - Rangeland. Small plots of irrigated agriculture are scattered throughout the subregion where reliable groundwater supplies are available.
4. **Vegetation** - Sand reed, big and little bluestem, sand dropseed, and sand sage.
5. **Soils** - Ustic Torripsamments, formed from aeolian deposits.
6. **Relative Surface Water Quality** - Few surface water drainages occur in this subregion, and these mainly are ephemeral. Groundwater quality is affected by the leaching of farm chemicals.

b. Moderate Relief Rangeland of the Western High Plains Ecoregion (map unit #25-2)

1. **Climate** - Semiarid. 200 to 300 mm of precipitation received annually.
2. **Physiography** - Irregular plains. Local relief is usually from 15 to 30 m, and sometimes 45 m.
3. **Land Use** - Rangeland.
4. **Vegetation** - Mainly blue grama, often occurring with western wheatgrass, galleta, alkali sacaton, and four-wing saltbush.
5. **Soils** - Ustolls and some Aridisols. Soils have formed from sediments.
6. **Relative Surface Water Quality** - Surface water resources are mainly intermittent and ephemeral streams. Exceptions include the Platte and Arkansas Rivers, which originate in the Southern Rockies Ecoregion. Quality is affected by stream bank and stream bed erosion due to highly erodible soils and trampling by cattle.

c. Flat to Rolling Cropland of the Western High Plains Ecoregion (map unit #25-3)

1. **Climate** - Semiarid. 200 to 300 mm precipitation received annually.
2. **Physiography** - Rolling plains. Local relief varies from a few to 15 m.
3. **Land Use** - Dryland crop agriculture.
4. **Vegetation** - Mainly blue grama, often occurring with western wheatgrass, galleta, alkali sacaton, and four-wing saltbush.
5. **Soils** - Ustolls.
6. **Relative Surface Water Quality** - Surface water mainly consists of intermittent and ephemeral streams and ponds. Perennial streams originate in the Southern Rockies Ecoregion to the west. Quality of surface and subsurface water is affected by runoff and seepage of farm chemicals, diversion of stream supplies for irrigation, and plowing of stream channels to improve field shape. The Platte River is particularly affected by severe water withdrawal, farm chemicals, and munipical and industrial wastes.

2.4.2.11 Description of the Southwestern Tablelands Ecoregion (#26)--

The semiarid Southwestern Tablelands are covered by grasslands, distinguishing the ecoregion from the more arid shrublands of the other tableland regions. The annual 250 to 500 mm of precipitation maintains plant communities dominated throughout most of the area by blue grama accompanied by western wheatgrass, galleta, alkali sacaton, four-wing saltbush, sand dropseed, sandsage, three-awn, bluestem sideoats, and grama. Yucca, piñon pine, and juniper are scattered in some areas. Grasses provide a mainstay for the grazing of beef cattle.

Topographic relief is tens of meters on irregular plains; however, high plateaus tower over river valleys more than 300 meters below. Soils receive meager inputs of moisture and organic materials and in many areas are subject to high rates of alluvial and colluvial erosion. Aridisols are widely distributed, and Torriorthents predominate where alluvial and aeolian-deposited materials have weathered in place.

The ecoregion contains mainly intermittent and ephemeral streams. The most conspicuous surface water resources are the Arkansas and Purgatoire Rivers, originating from the Rocky Mountains to the west. Unlike the steep-walled corridor of the Purgatoire River, the Arkansas is banked by gradual to irregular topography on either side. Irrigated agriculture occurs in gradual terrain immediately adjacent to the river.

2.4.2.12 Subregionalization of the Southwestern Tablelands Ecoregion--

Inspection of reference maps for this ecoregion revealed conflicting distributional patterns for environmental variables. We examined maps of vegetation, soils, geology, topography, annual precipitation, land use, suggested land use treatment, rangeland potential, and several types of published regional interpretations, yet found no clear relationships among mapped distributions of these characteristics. Experience has shown us that this occurs when changes in environmental features are too subtle to appear at our operational scale of resolution. The one unique feature was the irrigated agricultural corridor along portions of the Arkansas River. This divergent land use pattern was not reflected on any of the other reference maps. Because the feature represented only a narrow, discontinuous strip along the river, we elected not to distinguish it as a separate subregion. To sort out environmental variability in the Colorado portion of this ecoregion would require examination of characteristics at a finer resolution than that portrayed on the reference maps used for this study. Thus, the Colorado portion of the Southwestern Tablelands Ecoregion has been recognized as representing only one subregion. Were we to complete the delineation process beyond the borders of the state, it is likely that additional subregions would be identified.

a. Grasslands of the Southwestern Tablelands Ecoregion (map unit #26-1)

1. **Climate** - Semiarid. 300 to 400 mm of precipitation is received annually. A large area in the west central portion of the subregion receives less than 300 mm.

2. **Physiography** - Irregular plains and tablelands of moderate local relief, generally ranging between 15 and 30 m.

3. **Land Use** - Rangeland. An exception occurs along the Arkansas River where perennial water supply and areas of flat terrain are used for irrigated agriculture.

4. **Vegetation** - Mainly blue grama, often occurring with western wheatgrass, galleta, alkali sacaton, four-wing saltbush, sand dropseed, three-awn, sand reed, bluestem, sideoats grama, and yucca interspersed.

5. **Soils** - Ustollic Haplargids and Camborthids, and Ustic Torriorthents.

6. **Relative Surface Water Quality** - Surface water resources are mainly intermittent and ephemeral streams. Quality is affected primarily by rainwater runoff on highly erodible soils, and livestock trampling of stream banks and stream beds. The Arkansas River is affected by severe water withdrawal, runoff from farm chemicals, and municipal wastes.

2.5 SECTION SUMMARY

In this section, we have examined the reasons behind the development of an environmental regional framework by the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon. We have also described the steps used in the general process of delineating regions. Specific examples have been presented to demonstrate the rationale used to delineate regions at two different hierarchical levels.

In Section 3, we introduce several components relating to the evaluation of environmental data within the organization of a regional framework. The section covers various aspects within the major topics of data sources, quality, and screening procedures, and types of inventory and analyses that can be performed. Examples from actual state research projects are included.

SECTION 3

REGIONAL EVALUATION USING ENVIRONMENTAL DATA

3.1 INTRODUCTION

A major assumption in using the ecoregion framework is that it will improve our ability to account for much of the spatial variability in environmental features. To evaluate this assumption, we analyzed the correspondence between ecoregions and spatial patterns in physicochemical and biological components of stream ecosystems in Arkansas, Ohio and Oregon. In applying the framework for resource management or research, characterization of the regional features is necessary for drawing within- and among-region conclusions about the condition of resources. To this end, we used environmental data from Colorado and Minnesota to demonstrate methods to characterize ecoregions.

We draw on our experiences from these five state studies to present an overview of (1) data sources for regional evaluations, (2) data requirements for effective regional analyses, (3) regional sampling, (4) regional analyses of environmental data, including examples of results for many of the analyses, and (5) screening and use of available data, including recent examples using data from Colorado. All of our research relates to surface water chemistry and biological communities, though we believe the regional approach is applicable to other resources.

3.2 DATA SOURCES FOR REGIONAL EVALUATION

One option for evaluating regional patterns in environmental variables is to design and execute a research or monitoring program tailored for regions and variables of interest, such as selecting regional reference sites to characterize attainable quality. By *attainable* we mean the stream quality that could reasonably be achieved, as indicated by environmentally representative, least human-impacted streams. If we could isolate natural regional characteristics, regional baseline conditions could be measured. But since nearly all watersheds have some degree of human influence, we can measure only watersheds that are least impacted, as our closest approximation of undisturbed conditions. We recognize that least impacted sites do not represent undisturbed conditions, but rather provide the best information currently available about such conditions. We can thus demonstrate a level of environmental quality that it should be possible to attain under current land use conditions (Hughes et al. 1986; Hughes and Larsen 1988). Attaining quality surpassing this level would require more drastic alteration in land management practices.

In Ohio, for example, 107 minimally impacted streams in 5 ecoregions were sampled for water chemistry (16 monthly samples), fish (3 times), macroinvertebrates (1 time with 2 methods), and physical habitat (concurrent with biological sampling) (Larsen et al. 1986, 1988; Whittier et al. 1987; Appendix B). In Oregon, 99 minimally impacted streams in 8 ecoregions were sampled once for fish, macroinvertebrate and periphyton assemblages, water chemistry, and physical habitat (Whittier et al. 1988). In Arkansas, 37 stream sites in 6 ecoregions were sampled twice for fish, benthos, water chemistry, physical habitat, and flow data (Bennett et al. 1987; Giese et al. 1987; Rohm et al. 1987; Appendix B). Such surveys should assure thorough geographic coverage, consistent sampling, conscientious quality assurance/quality control (QA/QC), and optimum choice of variables and quality data. We estimate that these surveys require a two- to four-year commitment for planning, organization, and execution of the sampling, and for data analysis.

Another approach to evaluating regional environmental patterns is to use data available from a variety of sources. Examples include data bases from (1) Oregon, where fish collection data from 1,300 sites were evaluated for regional patterns (Hughes et al. 1987), (2) Minnesota, where data from approximately 1,100 lakes, collected over 6 years by several agencies were analyzed for total phosphorus and Secchi disk transparency in order to examine regional patterns in lake trophic state (Heiskary et al. 1987), and (3) Colorado, where water chemistry data (mostly from the U.S. EPA's STORET data base) and fish community data (from the state's Division of Wildlife and a variety of special studies and summaries) were analyzed for regional patterns.

Existing data offer several potential advantages, such as possible large numbers of sites and samples, historical perspective, great diversity of variables, relatively low costs (usually only to access a data base or transfer files, and to analyze the data), and short turnaround time between research design and data acquisition. There are also several serious limitations to consider before using available data for regional analyses: data quality assurance may be lacking or unknown, distribution of sampling sites and times may be inadequate or inappropriate, samples may have been collected for a wide variety of purposes using several potentially incompatible sampling and analytical methods, and sites may lack complete sets of variables. Thus, available data must be used with great caution and skepticism. One purpose of analyzing existing data for Colorado was to test the usability of available data to assess and characterize regional patterns. Many of the results presented in the discussion on available data are from this project, and serve as examples of the kinds of issues that occurred, the methodology developed to deal with them, and the outcomes of this methodology.

3.3 DATA REQUIREMENTS

In order for environmental data to be most useful, several conditions should be met, whether sampling is to be specifically designed for regional analyses, or data are obtained from existing sources. These conditions relate to geographic coverage of sites (distribution, number, levels of human induced impacts, and representativeness), the completeness of data (kinds of data and appropriateness of sampling), and data quality (of sampling and analyses). The importance of these factors varies, depending upon the purposes of the study. In many cases it will not be possible to fully meet the ideal conditions; thus, in the following discussion, the phrase *to the greatest extent possible* applies to each consideration.

3.3.1 Geographic Coverage

To characterize the environmental variables in a region, sampling sites should be spatially well distributed. Unless a high degree of statistical precision is desired, it is usually not necessary nor possible that an area be sampled at regular, or perfectly random, intervals. However, large areas devoid of sampling sites may not be sufficiently represented in the data set. Such cases may be unavoidable where the resource of interest is relatively rare, such as perennial streams in desert regions. Sites also should not be clumped in only a few portions of a region. Otherwise, data from a limited set of regional environmental conditions may be inappropriately construed to represent conditions over the entire region.

The ideal number of sites per region is a function of the natural variability in the area and the precision with which estimates are desired. Relatively small and/or homogeneous regions require fewer sites than large and/or naturally heterogeneous areas. Rigorous hypothesis testing and sampling for regulatory or litigation purposes require more sites than exploratory, baseline surveys. As the quality of, or confidence in, the data decreases, the number of sites needed increases. As few as six well chosen sites per region, with good quality assurance and quality control of sampling and analyses, may suffice to establish regional baseline data.

It is important to assess the level of human induced impacts on the environmental variables being studied. One of the major purposes of using an ecological regional framework is to stratify sampling to account for variability (noise) due to naturally occurring ecological differences. Human effects usually produce an additional level of data noise, potentially masking the natural regional differences. Thus if the data are to demonstrate attainable quality of relatively natural conditions, it is important that regional reference sites be as unimpacted as possible, though most regions have few, if any, pristine sites (Hughes et al. 1986). If the sampling is to demonstrate the range of anthropogenic impacts on natural regional conditions, then sites must be classified according to type and intensity of impact. This stratification of disturbance is necessary to confirm representation of the entire range of conditions. It cannot be assumed that just because a data base is large, a complete range of impacts is represented. For instance, most large government data bases emphasize areas of known impact, and most academic data are derived from studies avoiding impacted areas.

Sites selected for analysis of regional characteristics or potentials must also be representative of their regions, otherwise, the search for least impacted sites may lead to anomalous areas. For example, in a region characterized by deep soils and agricultural land use, an area of rocky outcrops may be left undisturbed (meeting the minimally impacted criterion) but could not be considered typical of the region. So considerations of *least impacted* and *representative* are often in conflict. Prior to site selection, it is necessary to understand the ecological characteristics of the regions and the occurrences of the features related to the environmental variables of interest. For example, in a study of lake trophic levels, if deep lakes are rare in a particular region, then it may be appropriate to either exclude them from the sampling or analyze them as a separate class.

3.3.2 Data Completeness

The kinds of data used in regional studies, their completeness, and their appropriateness are complex issues. The kinds of data needed for regional analyses vary with the complexity and scope of the project, and the amount of statistical sophistication and computerization intended. Many data requirements should be automatically met when a project includes its own sampling program. These needs can be scaled back for less complex projects, but should still be evaluated relative to overall goals.

Data completeness for regional analyses includes two components: the spatial representation of environmental conditions and the environmental variables sampled. Our general discussion of these issues is directed toward more complex data needs, assuming access to computerized data bases, statistical packages, and Geographic Information System (GIS) technology. Examples related to water chemistry and aquatic biology sampling are included.

Good locational data are essential for programs examining spatial patterns. If GIS mapping is used, sampling stations must have locations in one of three coordinate systems: (1) degrees, minutes, and seconds, (2) decimal degrees, or (3) Universal Transverse Mercator. In many parts of the country, and in many data bases, locations are in township, range, and section format. These data are not amenable to automated conversion to latitude/longitude coordinates, and must be approximately located on a map and converted by hand.

The following geographic information should be included in either the sampling site data or the GIS coverages, or both: (1) political location, such as state and county (a number of assessments have used counties as their spatial framework), (2) the name of the water body, (3) the hydrographic unit (similar to river basins; the units have been used in many research, monitoring and regulation programs), (4) the ecoregion (subregion may also be useful), and (5) a narrative site location description (clear enough for another person to locate the site on a map). There is also a variety of useful geographic information that could be included as independent variables, either as maps or as GIS coverages. These might consist of state designated uses of surface waters, locations of known point and nonpoint sources of impact, land use, and natural limiting factors, such as saline aquifers. These coverages would be valuable as overlays during the evaluation of regional patterns of dependent variables such as stream water chemistry or biotic assemblages.

It is important that environmental data collection be as complete as possible. Using stream water chemistry as an example, the following information should be available for each station: (1) the concentration of each chemical, (2) the number, date, and in some cases, time when samples were obtained, (3) the sampling and analytical methods used, (4) the flow rate (stream discharge) at each sample time, and (5) if possible, the purpose of the sampling (e.g., long-term monitoring, permit compliance). This additional information aids in the assessment of data completeness, appropriateness, and comparability among sites.

Likewise, complete stream biological data should include both fish and benthic macroinvertebrate collections, possibly augmented with periphyton (algae) and microinvertebrate collections. Biological data should also have supplemental information for each survey (list of sites), such as the person or agency responsible for the data, the purpose of the collection (e.g., for sport fish only, or selected families), the collection methods and dates, the quantitative or qualitative nature of the data, the level of taxonomic resolution for the specimens identified, and, for each site, the size of the area sampled and a description of the physical habitat conditions. Additional materials should be included about the species collected in order to extend the assessments. For example, description of the natural history, tolerance to perturbation (e.g., low dissolved oxygen, siltation), historical range, and possible stocking programs and introductions are useful in assessing the biotic health of a stream.

The appropriateness of environmental data for regional analyses is an issue when evaluating existing data, and should be emphasized during design of a regional sampling program and training of field crews. For example, if fish communities are to be sampled, it is important to emphasize that equal sampling effort must be directed toward all probable species, rather than toward sport fish. Similarly, if regional patterns in lake phosphorus are of interest, and one sample per lake is planned, then project objectives should dictate whether sampling is more appropriate during spring or fall turnover of nutrients, when the waters are well mixed, or during summer, when problem conditions are most likely.

3.3.3 Data Quality

Overall, data quality is receiving increased attention, especially as environmental, technical, legal, and fiscal issues become more complex. To be most effective, data should be of known quality. This can be achieved by establishing a quality assurance (QA) program for each project. The QA program begins by setting specific data quality objectives during the design phase of the project, which focuses attention on the levels of accuracy and precision needed and the trade-offs with cost. The QA program documents the quality control (QC) procedures to be used throughout all phases of data collection and analysis, including but not limited to, sampling methods, sample preparation and handling, laboratory methods (such as instrument calibration), duplicate and blank samples, and data entry. The QA plan should also include a statistically valid sampling design, as well as information on field crew training, equipment logistics, and methods for evaluating the results of the QC procedures. The overall program of QA and its QC procedures is often called QA/QC. Our experience indicates that data from existing sources often require considerable evaluation to determine the degree of quality and the appropriateness towards an intended use. Lack of consistent QA/QC during the transfer of field and laboratory data to computerized data bases is also a major impediment to using existing data bases. Screening of data is discussed in Section 3.6.

3.4 REGIONAL SAMPLING

A compromise between the cost of a project and the completeness of the data obtained occurs in all sampling programs. For water chemistry, the costs usually are related to the number of samples taken, and the number and complexity of laboratory analyses performed. For biological assemblages, costs relate to number of species and individuals collected and identified per sampling effort. The major expense for collecting fish assemblages is the sampling crew; usually a two- to three-person crew can sample one or two small stream sites or six to eight boat sampling sites per day. For benthos, one person can sample a site in about two hours; however, laboratory sorting and identification of the specimens can take several hours to several days per sample, depending upon the complexity of fauna and the level of resolution required.

Regional patterns in water chemistry may be portrayed as a snapshot of conditions during one season of a year, if based on single samples taken over a brief sampling period. For streams, conditions are usually most stable during summer low flows. Often, under these circumstances, water temperatures and concentrations of potentially detrimental chemicals are highest and the ecosystem is most stressed. For lakes, the most stable conditions occur during spring or fall turnover, when stratification breaks up and the waters are well mixed. The most stressed conditions occur just before spring or fall turnover, when hypolimnion oxygen concentrations are lowest. For the purpose of measuring the relationship between algal blooms and total phosphorus, lakes may be best sampled during summer. A snapshot approach of a single, one-season measurement of surface water quality was used in evaluating the ecoregions of Arkansas (Rohm et al. 1987) and Oregon (Whittier et al. 1988).

Long-term monitoring obviously costs more than one-time sampling, but provides a far more complete evaluation of regional conditions. Monthly stream sampling demonstrates the range of measurement values to be expected, as well as the seasonal patterns and stress periods. An average monthly or seasonal value calculated over several samples reduces the influence of unusual events, producing a more accurate assessment of site conditions.

The sampling needs for aquatic biology are somewhat more complex than for water chemistry. Each biotic group (fishes, benthic macroinvertebrates, periphyton, and microinvertebrates) has different sampling and analysis protocols. The following paragraphs present an overview of some sampling issues for the two most commonly sampled aquatic life forms, fish and benthic macroinvertebrates (benthos) in small streams. Sampling concerns are related to seasonality, completeness of sampling, and level of taxonomic resolution. The latter two are *level of effort* issues.

Aquatic organisms cannot be sampled with equal accuracy during all seasons of the year. For fish, mid or late summer to early fall is often the best period for sampling. At other times, the variability increases due to seasonal migrations or large numbers of *young of the year* fish. In addition, high flows during other seasons make the sampling difficult, if not dangerous. For benthos, the best time to sample is when most of the organisms have matured enough to be identified taxonomically, but not so late that the insects have emerged. In benthic communities, the species assemblages that are collectable and identifiable change throughout the year; therefore, it is important to sample at a consistent season in each region.

There is increasing evidence that, for most monitoring purposes, it is not necessary to perform a complete inventory (i.e., collect every individual) of fish assemblages, nor identify every benthic specimen to the species level. For example, ordinations of the benthic assemblages in the Oregon study showed similar regional patterns at the family, genus, and species level of taxonomic resolution (Whittier et al. 1988). Likewise, for purposes of characterizing regional biological assemblages, one or two collections taken annually during the optimum sampling season might be sufficient. In the Ohio study, reference sites were sampled for fish three times over one summer. When these data were ordinated using detrended correspondence analysis, the three samples from each site usually had each other as their nearest neighbors when axes I and II scores were plotted (Whittier and Rohm, unpublished data). That is, no major changes in fish assemblages occurred over the sampling season, and thus any one sample was representative of that site. Disturbed sites, however, have greater variance (Karr et al. 1986).

Whatever biological groups are sampled, it is important to sample for (collect, count, and identify) all subgroups whenever possible. As a counter-example, many fish collections have concentrated on, or reported, only sport fish. This practice provides an incomplete, biased picture of the whole community. If possible, all aquatic habitats should be sampled at a site, and an overall assessment of the watershed, stream, or lake physical habitat should be made to help evaluate the representativeness of the site and its biological assemblage(s). Examples of appropriate sampling protocols are those of Arkansas (Bennett et al. 1987; Giese et al. 1987), Ohio (Ohio Environmental Protection Agency 1987a, 1987b, 1987c), or the Rapid Bioassessment Protocols of the U.S. EPA (Plafkin et al. 1989).

3.5 REGIONAL DATA ANALYSIS

In the early stages of regional assessments (e.g., evaluation of correspondence between ecoregions and spatial patterns of ecosystems or selected environmental variables), data analyses are of a particularly exploratory nature. The emphasis is on developing a picture of the spatial patterns in the data to establish a baseline or range of conditions that characterize the regions. Because this kind of evaluation is not done in most areas, baseline conditions are probably unknown. If available data are being used, it may not be known whether the data are worthwhile. This analytical process is nonlinear and often iterative, requiring creativity along with objectivity, so as not to bias the analyses by recognizing only results or data showing desired patterns.

We employ a variety of data analyses and presentation techniques, primarily dot maps, boxplots, ordinations (e.g., principal components analysis, detrended correspondence analysis), and species signatures (profiles). These analyses are somewhat redundant, but each provides another way of demonstrating and assessing regional patterns in the data. The visual displays resulting from these techniques are more quickly and completely comprehended than tabular presentations.

3.5.1 Water Chemistry Analysis

Univariate analysis of water chemistry data should be the first step in regional assessment of water chemistry. This allows us to develop an understanding of the components before moving on to more sophisticated procedures. At each site, a value is determined to represent that location for each chemical or physical variable. For data from one-time sampling, that value is obvious. For multiple sample programs, the median site value for each variable is preferred over the mean, because the median is less influenced by a few extreme values than is the mean. It is also useful to determine seasonal median values (e.g., summer or low flow vs. all year).

We use dot maps to portray spatial patterns of individual chemical variables across the regions being studied. An effective way is to draft a map, with outlined circles at each sampling location (we call these dot maps), to serve as a template for duplication. For each variable, the range of values is examined and partitioned into from 2 to 10 groups or classes. These divisions may be based on a variety of criteria, for example, presence or absence of values above a given standard, commonly used classes, such as lake trophic state, or equal-sized groups. The number of classes depends on the purpose of the study and the level of resolution desired. We find that six to nine classes provide good resolution for many purposes; fewer classes may limit the ability to perceive gradations in the patterns of the data; the use of more classes is restricted by our inability to portray and instantly discern a larger range of symbols or colors.

We prefer to produce a map for each variable by coloring in the circles with a progression of hues, usually lighter to darker, to indicate classes of increasing data values. However, since publishing in color is expensive, some alternatives are to use a set of symbols, sequence of numerals, or progression of grey tones. Figure 3-1 shows median stream concentrations of total phosphorus in Ohio's regional reference sites. This figure depicts regional patterns in a manner that can be quickly and clearly comprehended. Patterns of the spatial distribution of the classes can be compared with patterns of other environmental variables, such as soils, geology, and land use, to determine apparent associations. Generalizations can be made concerning which environmental characteristics are common among the data points for a particular map class.

Another univariate tool with which to begin quantifying regional patterns is the boxplot (e.g., Figure 3-2). Boxplots display the central measures of concentrations for each variable for each region. These measures can include the average (median, mean, or both) and central ranges where most values fall, the interquartile range, and sometimes the standard deviation or standard error. Boxplots may show additional information about the distribution of values, such as the 10th

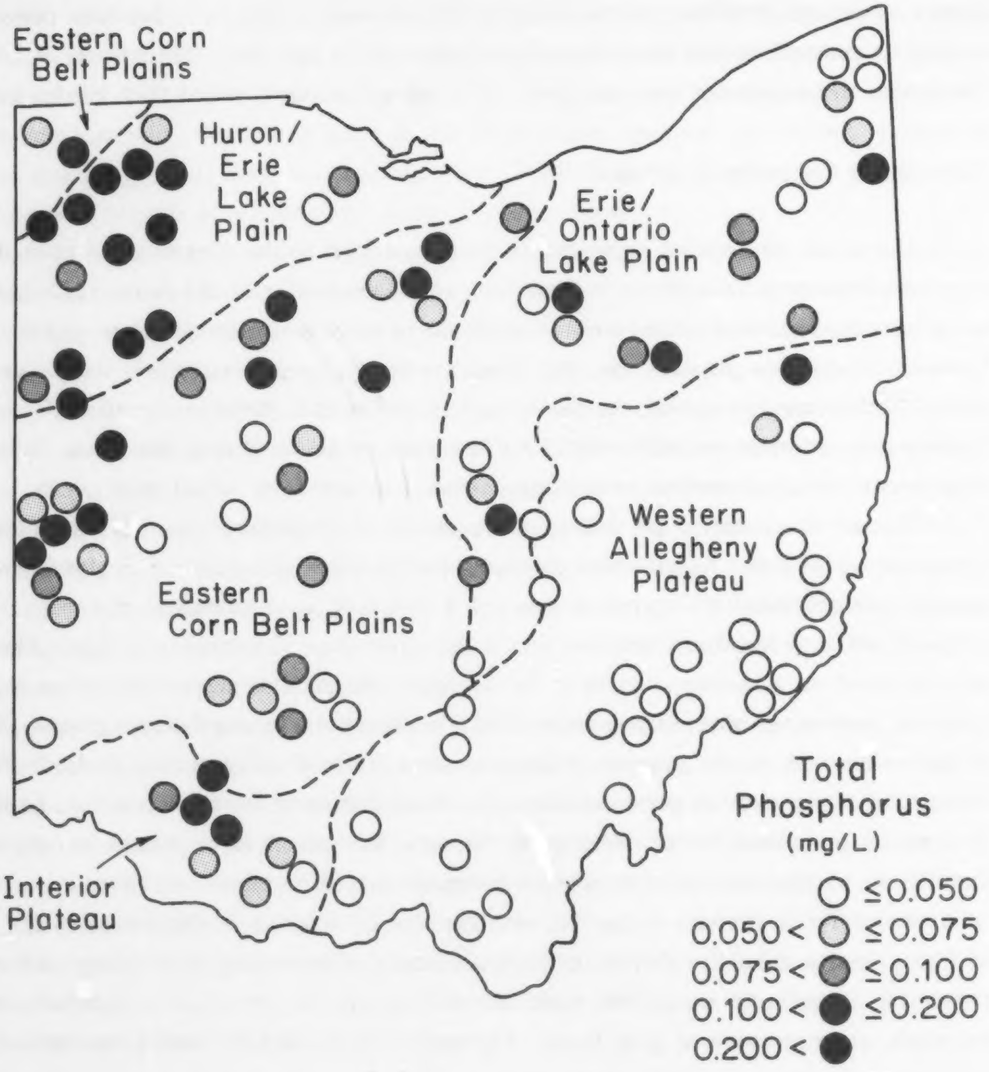
Eastern Corn Belt Plains
Huron / Erie Lake Plain
Erie / Ontario Lake Plain
Western Allegheny Plateau
Eastern Corn Belt Plains
Interior Plateau
Total Phosphorus (mg/L)
○ ≤0.050
0.050 < ○ ≤0.075
0.075 < ● ≤0.100
0.100 < ● ≤0.200
0.200 < ●

Figure 3-1. Spatial patterns of total phosphorus in Ohio streams. Values are site medians of monthly samples taken over a 16-month period (Larsen et al. 1988; Whittier et al. 1987).

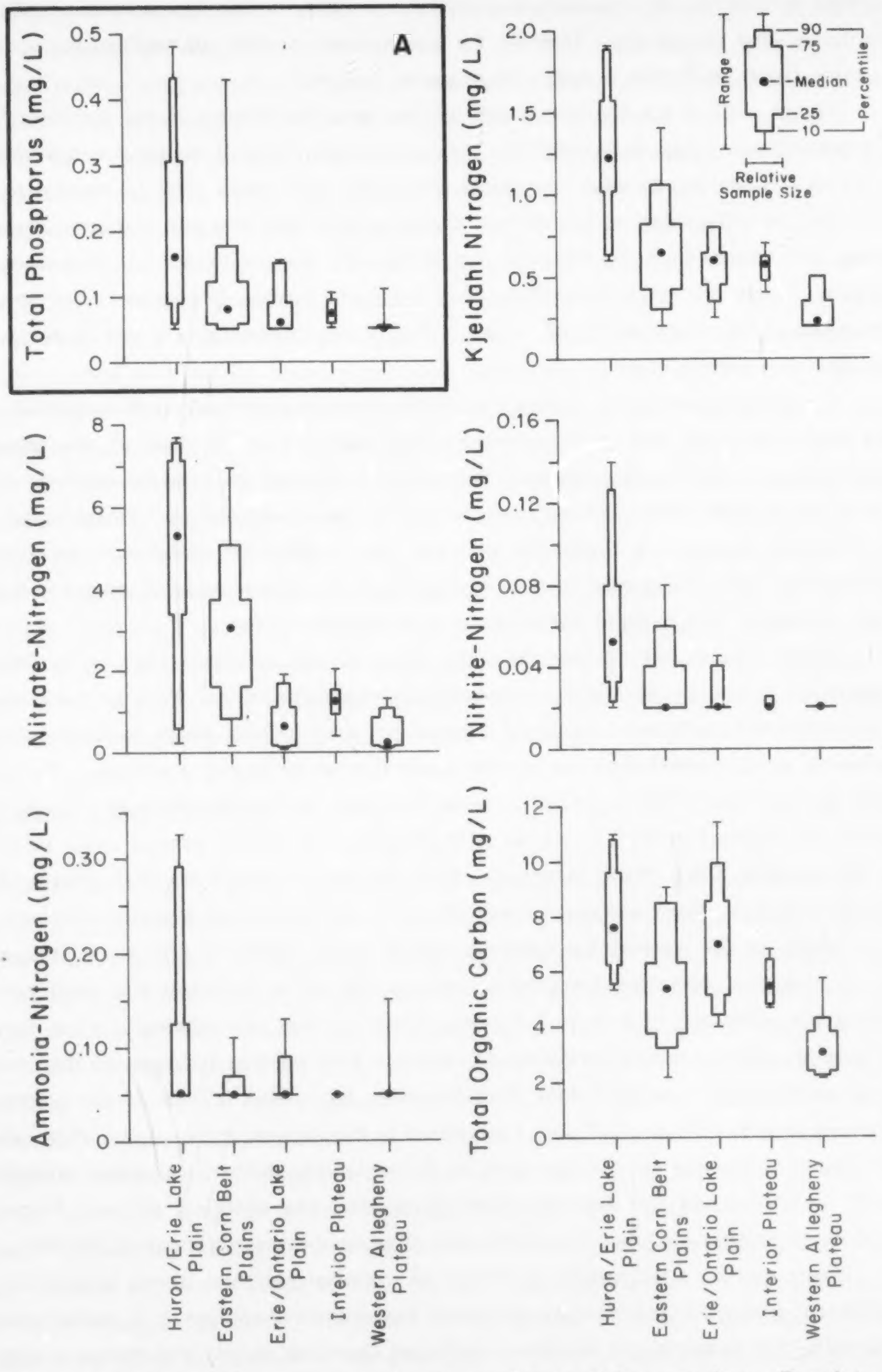

Figure 3-2. **Selected nutrient measures of water quality in Ohio ecoregions. Boxplots are of site medians of 16 monthly samples (Larsen et al. 1988; Whittier et al. 1987).**

and 90th percentiles, the minimum and maximum values, outliers beyond some confidence limits, and the relative sample size. Usually, for a particular variable, all regional boxes are drawn on the same figure to facilitate comparisons among regions.

Figure 3-2a is the boxplot display of the same data shown in the previous figure. This data presentation begins to quantify the regional characteristics of variables and indicates the level to which the regions account for spatial variation. Dot maps tend to emphasize the regions dominated by either high or low values. Boxplots show this, but also bring out the relationships among the intermediate or transitional regions and those with a high degree of variability. Boxplots display enough of the information contained in data frequency curves to also indicate distortions in the distribution of values. The basic information in the plots may be easily extracted into tabular form.

Concentrations of many chemical variables are often moderately well correlated, thus regions with high values in one variable tend to have high values in most of the others. To aid interpretation of the regional patterns, it is useful to arrange the regional boxplots in order from high to low concentrations and to group plots of several related chemical variables into one figure. For example, Figure 3-2 shows the boxplots for six nutrient enrichment variables in Ohio's reference streams. This grouping of plots displays the consistent regional pattern commonly found across variables, with a slight variation for total organic carbon.

When water chemistry data are taken from regional reference sites, as in these examples, boxplots are useful for displaying regionally attainable conditions. Because the sites are located in representative, minimally impacted watersheds, they portray water chemistry that should be achievable given current land use practices and natural ecological conditions. For instance, the upper quartile limit (75th percentile) might be chosen as the regional goal. Thus, according to Figure 3-2, regional criteria levels for total phosphorus in Ohio's streams could be 0.30 mg/L in the Huron/Erie Lake Plain Ecoregion, 0.12 in the Eastern Corn Belt Plains, 0.10 in the Erie/Ontario Lake Plain and the Interior Plateau, and 0.05 in the Western Allegheny Plateau.

There are also methods for examining the regional patterns in several variables at once. For water chemistry, principal component analysis (PCA) is probably the most useful of the multivariate analyses. PCA is an ordination technique that can collapse a set of correlated data into one or a few variables (principal components) that account for most of the variability in a set of multivariate correlated data (SAS Institute, Inc. 1985). Thus, if the concentrations of chemicals shown in Figure 3-2 are as correlated as they appear to be, then a PCA could generate one composite variable to represent most of the variability in the six nutrient variables. Because the PCA is designed for normally distributed data, the chemical data in Figure 3-2 were transformed using a log (x+1) transformation to achieve a more normal distribution.

There may be a temptation to analyze all chemical variables in one large PCA. However, if different groups of variables have different environmental sources, it is useful to analyze them separately. For example, the nutrient enrichment chemicals mostly had human origins, while the ionic strength measures (e.g., conductivity, alkalinity, hardness) were generally derived from soil, bedrock, and sometimes aquifers. When we subjected these nutrient data to a PCA, the first principal component (PCA I) accounted for 64% of the data variability. The PCA I scores corresponded to increasing concentrations for all variables. The second principal component (PCA II) accounted for an additional 14% of the variability, and reflected the dominance of total organic carbon. The PCA I seemed to express the overall quality of nutrient richness of the stream water. The ionic strength measures were more highly correlated than the nutrient enrichment variables. As a result, the ionic strength PCA I accounted for 90% of the variability.

The results of the two principal component analyses can be summarized as a graph of the PCA I for nutrient richness versus the PCA I for ionic strength (Figure 3-3). Sites having similar PCA scores, those close to each other on Figure 3-3, have similar chemical concentrations. This graph shows a clear relationship between the water chemistry of the sites and their ecoregions. Sites in the Western Allegheny Plateau are clustered in the area of low nutrient richness and low to intermediate ionic strength. Sites in the Interior Plateau form a close group, with intermediate values for both groups of variables. Sites from the Erie/Ontario Lake Plain are more scattered and encompass those of the Interior Plateau. Sites in the Eastern Corn Belt Plains have the highest overall ionic strength, while the Huron/Erie Lake Plain sites have the highest nutrient richness.

Each of the Ohio regions could be distinguished by a combination of nutrient richness and ionic strength variables. Groupings that define attainable water chemistry in minimally impacted streams of each ecoregion can be indicated by the enclosed areas in Figure 3-3. These areas have been subjectively circumscribed to indicate the general regional water chemistry. Although not all sites fit this general pattern, regional differences are evident.

3.5.2 Analysis of Aquatic Biota

With biological data it may be less important to perform strictly univariate analyses before multivariate data analyses. That is, it may be most valuable to run a number of species ordinations initially to obtain a sense of the overall regional patterns, prior to calculating regional indices. To organize our discussion, we present methods of univariate analyses first. Any analysis that produces a single value per site can be plotted onto a dot map and presented in regional boxplots to display regional patterns in biological assemblage measures, as discussed for water chemistry data. However, for data from small streams, index values may also be affected by the stream size, so two other techniques are reviewed here: regressions and boxplots of residuals.

Regional assessments of biological data should include any of a number of indices that measure the health or integrity of the biological communities. These indices are somewhat multivariate because they include information from several variables in the calculations. However, the indices usually produce a single number for each site and most of the calculations can be performed on a handheld calculator. The following examples of biological indices are drawn from stream fish community analyses, but the principles on which they are built apply to other organism groups.

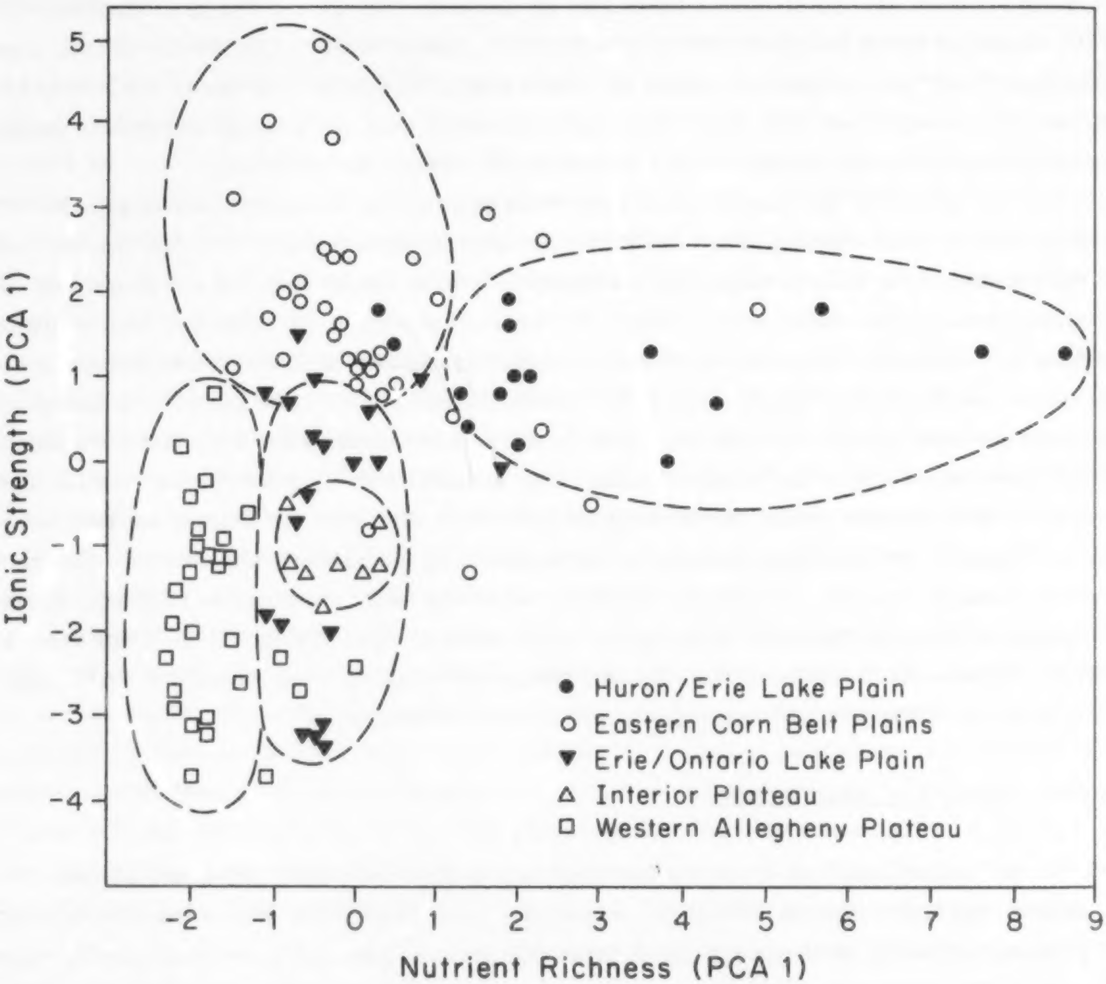

Figure 3-3. Regional patterns in nutrient richness and ionic strength variables measured in Ohio streams, as indicated by principal component analysis axis I scores for each. Areas enclosed indicate hypothesized attainable water quality for each Ohio ecoregion (Larsen et al 1988; Whittier et al. 1987).

Species richness (the number of different species) is a simple and direct measure of the variety of species present in a community If exotic (non-native) species are excluded, greater species richness indicates better ecosystem health, in most ecoregions. In general, species richness in small- to medium-sized streams increases as stream size increases. Because of this relationship, dot maps and boxplots of the raw species richness values for Ohio data would include variability attributed to this source. Therefore, we regressed species richness on watershed area, as a measure of stream size (Hughes and Omernik 1983), then examined residuals from this relationship for regional patterns. This analysis (Figure 3-4) shows that for watersheds of similar size, species richness tends to be lowest in the Huron/Erie Lake Plain and highest in the Western Allegheny Plateau.

As with any of these analyses, regressing an index value against another variable must make ecological sense if it is to be useful. For example, in Ohio, rainfall and runoff patterns are relatively similar statewide, but in Oregon, annual rainfall varies from less than 250 mm to greater than 2,500 mm across the state. Thus, watershed size is a better estimate of relative stream size in Ohio than in Oregon.

Species diversity is a commonly used community index that combines species richness and equitability, the relative abundance of species. This index was linearly related to watershed area in the Ohio study. There is growing evidence that species diversity is not particularly meaningful as a community index, despite its popularity (e.g., Hurlbert 1971; Washington 1984).

For fish communities, especially in larger streams and rivers, Gammon's *Index of Well Being* (IWB) is a useful measure of biological health. The IWB combines measures of abundance and biomass, and the diversity of the two. This index appears to reflect environmental quality more satisfactorily than does species diversity alone (Gammon 1976, 1980; Hughes and Gammon 1987). In Ohio's streams, there is a slight but significant relationship between stream size and the IWB.

Other measures of the health of an ecosystem include the number of species and the fraction of individuals in the community that are generally intolerant of environmental degradation. In streams, intolerant species are generally those requiring high levels of dissolved oxygen and low levels of turbidity and siltation. In the Ohio study, all of these indices of community health (diversity, IWB, percent intolerant individuals, and number of intolerant species) showed regional patterns similar to those seen for species richness.

Recently, another measure of community health, the *Index of Biotic Integrity* (IBI), was developed for streams in the Midwest (Karr 1981). The IBI sums the values of 12 individual metrics that evaluate different facets of the community structure related to ecosystem health. Essentially, the IBI quantifies the kinds of judgment that a professional biologist would make when assessing the health of streams in a particular region. The IBI is considered to be more robust than any single measure we have discussed (Karr et al. 1986; Miller et al. 1988; Plafkin et al. 1989). The concept and process can be transferred to other organism groups, ecosystems, and regions (Miller et al. 1988; Hughes and Gammon 1987). In Ohio, the IBI scores (Figure 3-5) follow the same regional patterns as the other indices discussed earlier in this subsection.

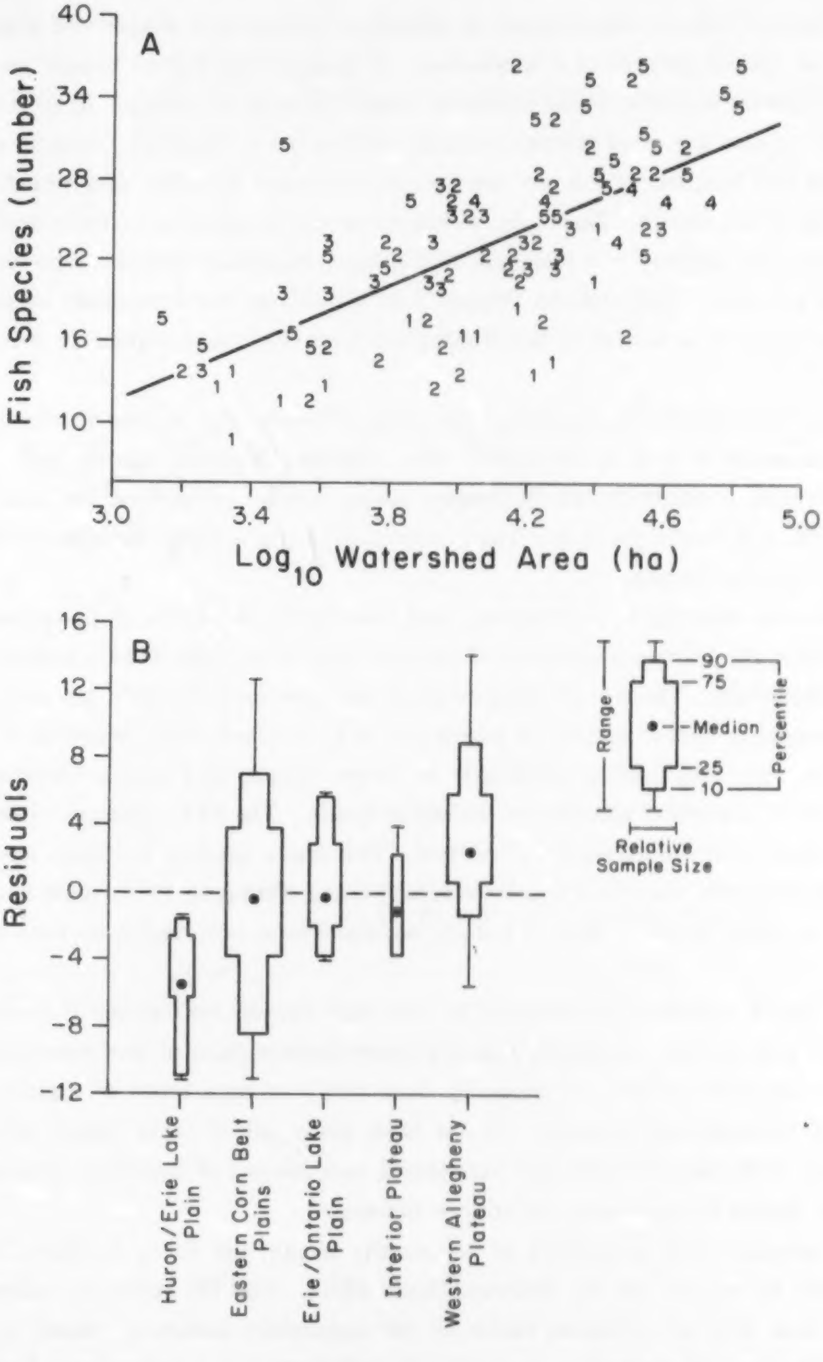

Figure 3-4. Fish species richness of streams in Ohio ecoregions. (A) Regression of maximum fish species richness at each site vs. $\log_{10}$ watershed area: 1 = Huron/Erie Lake Plain, 2 = Eastern Corn Belt Plains, 3 = Erie/Ontario Lake Plain, 4 = Interior Plateau, 5 = Western Allegheny Plateau. (B) Boxplots of the residuals of the species richness regression by region (Whittier et al. 1987).

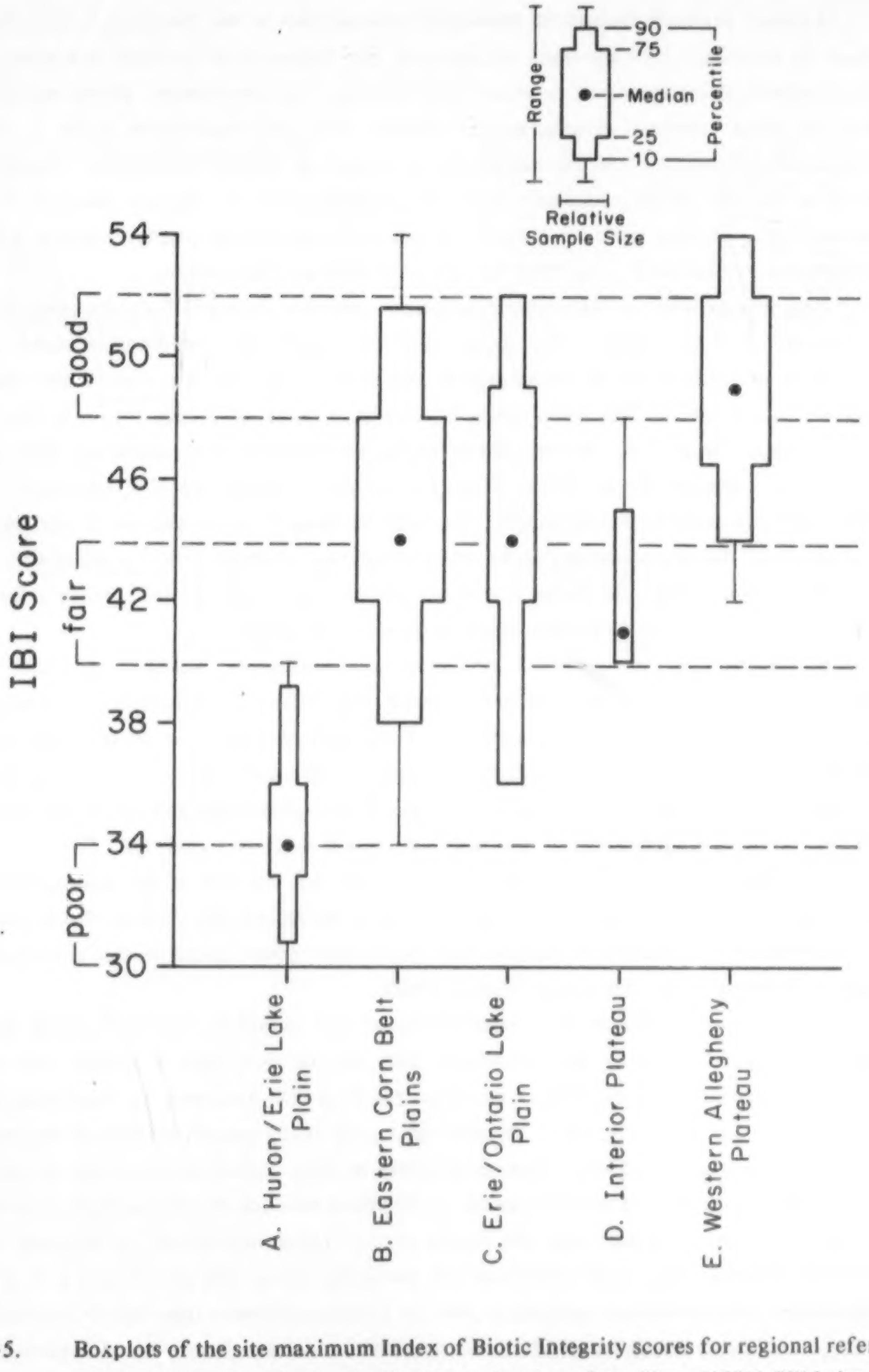

Figure 3-5. Boxplots of the site maximum Index of Biotic Integrity scores for regional reference sites in Ohio ecoregions. Qualitative evaluations from Karr (1981) (Whittier et al. 1987).

Another regional feature of biological communities is the distribution and dominance of species or families. One approach to assessing this feature is to produce dot maps of the sites where individual species occur or where they dominate the assemblage. However, in cases where there are large numbers of species, the number of maps proliferates quickly. This species distribution information can be succinctly presented as species signatures. These figures are analogous to the pollen diagrams used by paleobotanists to display changes in vegetation communities over long periods of time. In this case, the figures display regional differences in the biological communities expected in relatively unimpacted streams.

Regional patterns in the common organisms may be displayed by frequency of occurrence, by dominance, and by relative abundance. For these methods, there must be some way to select the species or families to be included. In the Ohio study, for the relative abundance species signature, those species that had a mean relative abundance of at least 2% in at least one region were included (Figure 3-6). For the dominant species signature, dominance was defined as greater than 10% of a sample (Figure 3-7). These figures show that two species, bluntnose minnow and creek chub, are ubiquitous and usually dominant in small Ohio streams in all regions. However, there are clear regional patterns for the other commonly collected fish. In areas with few species (e.g., the western states), the frequency of occurrence (percentage of sites where a species occurs) may be the best method to display regional patterns of species.

Biological data can also be subjected to multivariate analyses to show the overall relationships among sites based on their species composition. Various cluster analyses may be used, but these rarely, if ever, produce neat regional clusters, and so may distract from the assessment of regional patterns. Ordination scores can be used to plot, in two or three dimensions, the relative locations of sites in species space. Thus, ordinations can show the overall pattern without including the statistically imposed breaks seen in cluster analyses. Principal components analysis ordination can be used with biological data, but because of the nonlinearity of species data, most biological data suffer two separate distortions during this process. Reciprocal averaging and detrended correspondence analysis mathematically remove most of this distortion, with the latter performing somewhat better (Gauch 1982).

There are a number of data transformations that should be explored during ordination of biological data. Of course, raw abundance data can be used, but if counts vary over several orders of magnitude, the ordination scores on the first few axes may be dominated by the high abundance of one or two species. In this case, a log (x+1) transformation of the counts should be tried. The presence/absence form of the data is often useful, but collections with many rare species may also produce distorted results. Ordinations may also be run on biological data grouped by family or genus. In any case, the results of the ordinations should be carefully examined to determine whether they make ecological and biological sense. Figure 3-8 is a plot of axes 1 and 2 detrended correspondence analysis scores for presence/absence data for fish from the Oregon study. Axis 1 separates the mountainous ecoregions from the nonmontane ecoregions. The second axis generally separates the three nonmontane ecoregions from each other.

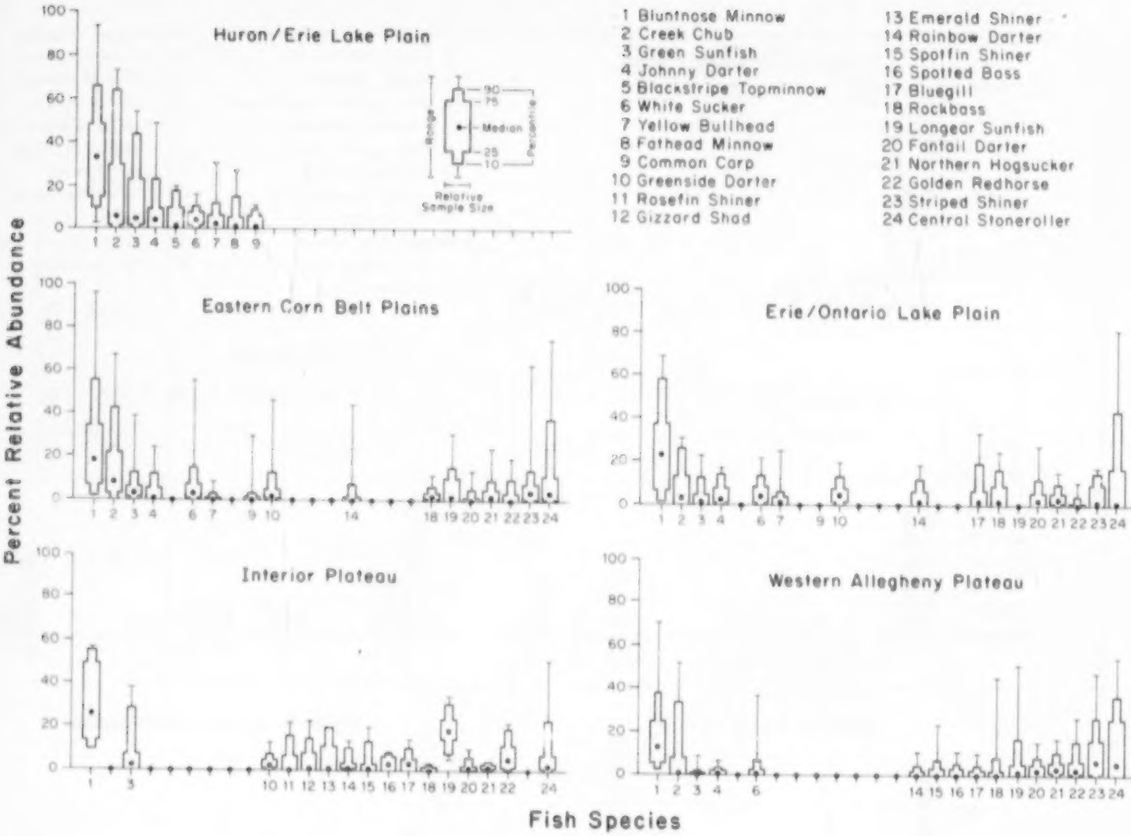

Figure 3-6. **Relative abundances of 24 fish species in Ohio ecoregions. For each region, only those species found in at least 50% of that region's samples are plotted (Whittier et al. 1987).**

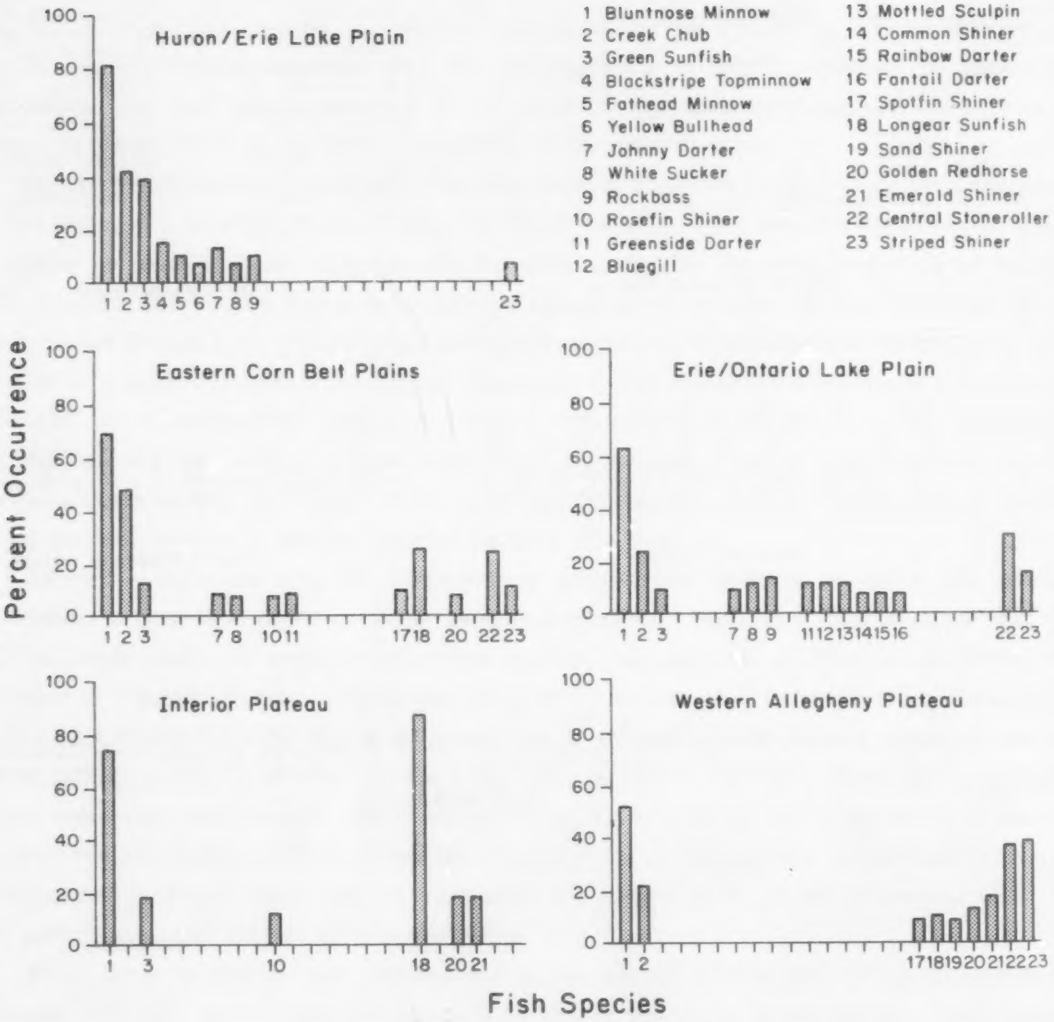

Figure 3-7. Dominant fish species in Ohio stream samples. Fraction of samples in which these 23 species comprised more than 10% of a sample (Whittier et al. 1987).

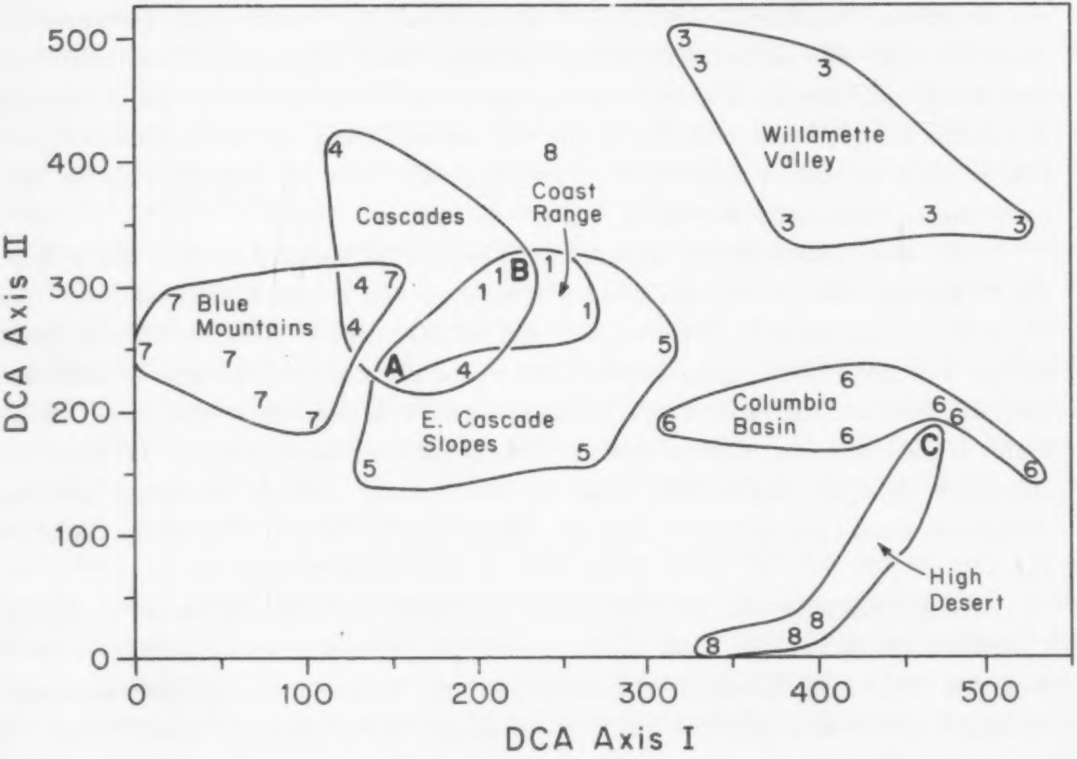

Figure 3-8. **Ordination showing regional differences in fish assemblages of 51 representative, minimally impacted Oregon streams. The assemblage of fish expected for an additional regionally representative stream should be within or near the area circumscribed (Whittier et al. 1988). A = eight sites with 100% *Oncorhynchus mykiss* (five in Sierra Nevada, one each in Cascades, Eastern Cascade Slopes, and Coast Range). B = five sites with only *Oncorhynchus mykiss* and *Cottus perplexus* (two in Eastern Cascade Slopes, one each in Cascades, Sierra Nevada, and Coast Range). A and B include all Sierra Nevada sites. C = two High Desert sites in the Columbia River drainage.**

3.6 SCREENING AND USING AVAILABLE DATA

There exists a vast amount of environmental data that could be useful for the kinds of regional analyses discussed here. These data have been collected by a wide variety of agencies and institutions for an equally broad array of purposes. For example, state governments collect water chemistry data for drinking water assessments, waste water permit compliance, long-term monitoring, and detection of undocumented impairment. They also collect aquatic biological data to maintain sport fisheries, check for aquatic life use impairment, and monitor ambient conditions. Similar sorts of aquatic resource data collections are made by federal, regional, and local governments, educational institutions, and private agencies.

The sheer volume of data demands some process for selecting a subset that is appropriate for the current purpose. Another concern about these data must also be considered. Generally, the level of data quality is unknown, and may be unknowable. This implies that considerable caution is needed. For any given geographic area, the available environmental data will have been obtained, analyzed, and reported in a variety of ways. This means that, unless data from only one source is used, a strong effort is needed to check for comparability and to bring the data into compatible formats. All of the issues discussed earlier, such as geographic coverage, data completeness and appropriateness, and data quality, need to be considered in the use of available data.

Subsections 3.6.1 and 3.6.2 discuss an evaluation and characterization of ecoregions in Colorado based on available water chemistry and fisheries data. This example illustrates how we evaluated these data, the specific kinds of problems encountered, and their solutions. This material is meant as a specific example of the generic issues related to using available data and not as an indictment of any particular agency's sampling or data. Similar concerns should be anticipated whenever existing data are used.

3.6.1 Available Water Chemistry Data

The U.S. EPA maintains a very large, nationwide data base of water chemistry data known as STORET. The data are supplied by federal, state, regional, and local agencies from their sampling programs. This data base generally is the most extensive source of water chemistry information available and has been our primary source of water chemistry data for our study on Colorado streams. There is no one entity with QA/QC oversight for data entered into this system.

There are approximately 21,000 STORET sampling stations of various types in Colorado. To simply list all of the stations, with no water chemistry data, would produce nearly 3,000 pages of printout. Moreover, samples have been collected at some of these stations monthly for 20 or more years. It would not be possible, necessary, or advisable to work with all of the Colorado water chemistry data in STORET. There are many ways to extract data from STORET that restrict the number of stations for which data are retrieved. Our final choice of retrieval methods was the result of a trial and error exploration of various subset retrievals, aimed at selecting data more directly applicable to our purposes.

The initial phase of examining the data base was guided by questions concerning the spatial distribution of sampling stations, the kinds of chemicals analyzed, the most useful method of STORET data retrieval, the transfer of station data into a GIS for mapping, and so on. We looked for a balance between the level of detail needed and the level of effort we could afford. Most helpful for this process was a combination of software tools that (1) selected sites by location (latitude/longitude, county, and hydrologic units), (2) selected sites by station type (e.g., ambient stream, lake, outfall) and whether chemicals on the U.S. EPA priority list were analyzed, and (3) provided summaries of data, and listings of station information headers.

We experimented with a variety of retrievals for relatively small geographic areas (county, hydrologic unit, one-degree-by-one-degree block) and data formats (e.g., summaries of all variables for small sets of stations and basic statistics for selected chemicals and stations). These retrievals were hand-checked for number and type of stations, kind and amount of chemical data retrieved, and location of stations. We decided, for assessing regional patterns of water chemistry, to limit retrievals to ambient stream stations. Other stations, such as natural lakes and wetlands, are relatively rare in Colorado, are dependent on groundwater sources (springs, wells), or are impacted by human activity (reservoirs, outfalls).

These initial retrievals suggested that the distribution of STORET stations was very uneven across the state. There was also evidence of a high error rate in the locational data. If the retrieved data were to be automatically entered into a GIS for mapping, then the locational data needed to be accurate. We ran a retrieval of station header data for all ambient stream sites, resulting in about 4,800 stations, to assess the distribution of sampling stations and the quality of the locational data.

About 200 of these stations had no latitude/longitude data (essential for GIS mapping) and about 800 had no county codes. The remainder of the stations were listed in county code order, so rough estimates of data availability were made by county (Figure 3-9). Of the 63 counties in Colorado, 13 had fewer than 15 stations, including 4 counties with no ambient stream stations. This demonstrated an uneven coverage of the state; large areas with almost no available ambient stream chemistry data coincided with areas of very low annual rainfall and low stream flows.

A 4% sample from the ambient stations listing was hand-checked for errors in latitude/longitude, county, hydrologic unit, and station type against the actual location of the station description on 1:500,000- and 1:24,000-scale U.S. Geological Survey topographic maps. About 8% of the stations checked had location names indicating they had been improperly coded as ambient stream sites (lake sites, industrial effluent samples, storm sewer outfalls, wells, and sediment samples). Another 8% had no location description at all. About 10% of the station names were for streams that did not appear on any of our maps. Of the remainder of the sample, about 10% had latitude/longitude locations that fell more than one mile from the appropriate stream course on the map, most occurring four to six miles from the stream. Two stations were

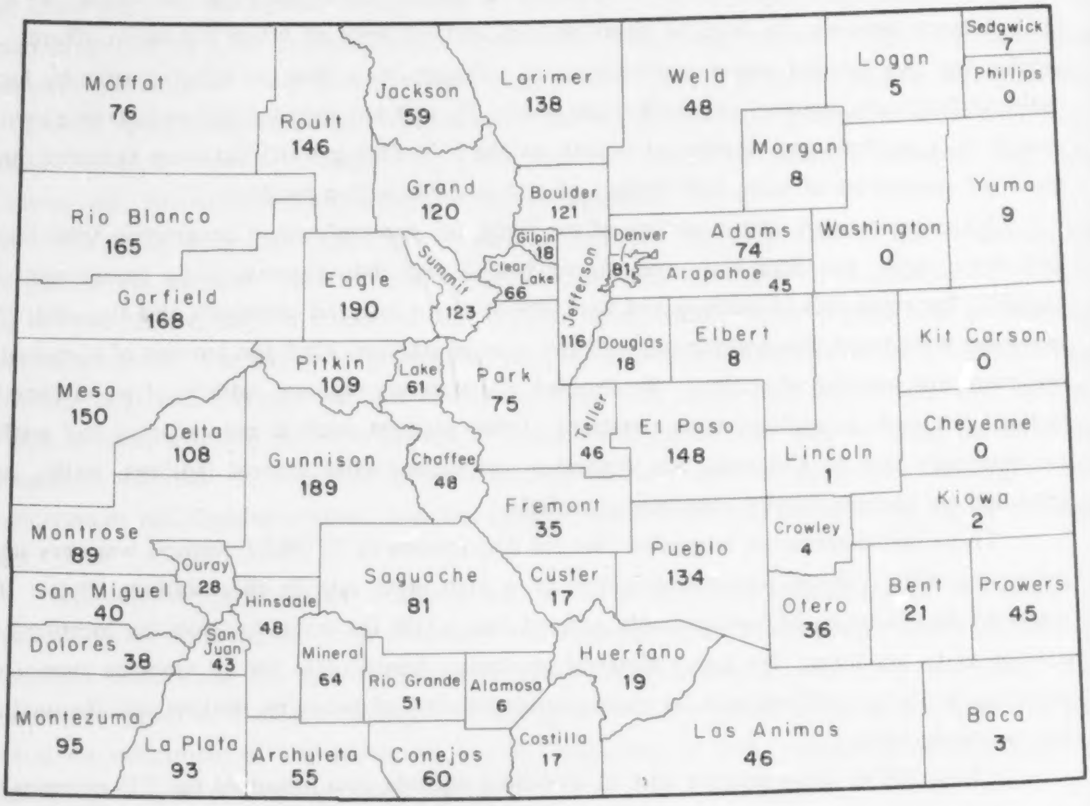
Sedgwick 7
Phillips 0
Logan 5
Weld 48
Larimer 138
Jackson 59
Moffat 76
Routt 146
Morgan 8
Yuma 9
Grand 120
Boulder 121
Rio Blanco 165
Gilpin 18
Denver 81
Adams 74
Washington 0
Summit
123
Clear Lake 66
Jefferson
116
Arapahoe 45
Eagle 190
Garfield 168
Douglas 18
Elbert 8
Kit Carson 0
Pitkin 109
Lake 61
Park 75
Mesa 150
Teller
46
El Paso 148
Cheyenne 0
Delta 108
Gunnison 189
Chaffee 48
Lincoln 1
Kiowa 2
Fremont 35
Montrose 89
Crowley 4
Pueblo 134
Ouray 28
Saguache 81
Custer 17
Bent 21
Prowers 45
San Miguel 40
Hinsdale 48
Otero 36
Dolores 38
San Juan 43
Mineral 64
Huerfano 19
Rio Grande 51
Alamosa 6
Montezuma 95
La Plata 93
Archuleta 55
Conejos 60
Costilla 17
Las Animas 46
Baca 3

Figure 3-9. Number of STORET ambient stream stations in Colorado counties.

more than 35 miles off the appropriate location. About 3.5% of the stations had incorrect hydrologic unit codes, and one station had the wrong county code.

Excluding the stations that could not be located on the maps, the overall error rate was about 25%. Other errors were observed outside of this sample, including cryptic station descriptions. In an extreme example, 90% of the stations coded for Baca County were actually in Gunnison County, an error of more than 300 miles. Based on this assessment, we hand-checked every STORET site retrieved before we transferred the data to the GIS.

A second difficulty with the STORET data is the wide variety of parameter codes (indicating chemicals and analyses) from which to choose during selection of chemical data. This reflects the continuing development of new methods by the scientific community and the attempts to accommodate these developments through alterations to the data base. Although this flexibility is important, it has implications for assessing regional patterns in water chemistry. First, data measuring the same impacts may not be directly comparable across sampling and analytical methods. Second, the problem of choosing parameter codes and/or deciding on some combination of codes for the same chemical or impact becomes complex. This effectively reduces the amount of useful data. Third, there may be no parameter code that matches directly with a particular generic problem. For example, *Total Dissolved Solids* is an item of major concern in western Colorado, yet there is no STORET variable code for Total Dissolved Solids. Instead, there are at least 10 codes that appear to be related to that issue (Table 3-1).

Many of the nutrient measures have an equally bewildering array of codes associated with different ways of quantifying nutrients. As an example, in one listing of only 89 stations there were 22 different ways of measuring and reporting nitrogen. For metals, there was often a choice of dissolved, suspended, total, and total recoverable. The parameter codes eventually chosen for our analyses were those that, from our "test" retrievals, had the largest number of samples and appeared to be what we needed. Our final method for extracting data from STORET was based on these considerations: (1) STORET station headings contained a high percentage of error, so each station had to be hand-checked for location and station type, (2) STORET output files had to be reformatted before they could be used directly by the GIS, (3) most stations had sample measurements on a minority of the variables of interest, although conductivity, alkalinity, and hardness were sampled at many stations, and (4) many stations were sampled only once. We were further concerned about changes in analytical methods over time and about combining data gathered over a long span of time.

Our initial aims were to produce dot maps of single variables and to use the GIS data base to extract values for boxplots to show the spatial (regional) distribution of chemical values. We retrieved station-by-station summaries of the selected variables. We requested median values over all samples taken in the last 10 years (since January 1978) from all ambient stream stations that had ever been sampled for any of the codes in one of the three variable groups we used: metals (cadmium, zinc, lead, mercury, and copper), nutrients (nitrate/nitrite-nitrogen, Kjeldahl-nitrogen, total ammonia, total phosphorus, and two orthophosphate measures), and miscellaneous (total

Table 3-1. STORET Parameter Codes that Appear to be Related to Total Dissolved Solids Concentrations Based on Selected Retrievals of Ambient Stream Stations in Colorado

Parameter Code	Computer Printout Abbreviation
(00500)	Residue -- Total
(00505)	Residue -- Tot Vol
(00515)	Residue -- Diss-105C
(00530)	Residue -- Tot Nflt
(00545)	Residue -- Settlable
(70299)	Red-Susp at 180C
(70300)	Residue -- Diss-180C
(70301)	Diss Sol -- Sum
(70302)	Diss Sol -- Ton/day
(70303)	Diss Sol -- Tons/Acre-ft

dissolved solids and suspended sediments). We extracted separate files for each group. Because the ionic strength measures (conductivity, hardness, alkalinity) were collected at most stations, we also retrieved median values of these with each group. In the long run, it may have been more effective to have extracted all data into one file, but it was initially easier to process relatively small files of related information; also, we needed to experiment with a small file on the GIS to assess the value of this approach and these data.

We wrote a FORTRAN program to modify the STORET output into a tabular (list) form suitable for transfer to the GIS. Printouts of these files were hand-checked for locational errors as discussed earlier. Sites with descriptions that were cryptic or missing, or that referred to something other than ambient streams, were removed from the files. The latitude/longitude data were located on maps and compared with the station descriptions. Stations with latitude/longitude coordinates within one mile of the appropriate stream course were accepted. A few stations had what appeared to be single-digit data entry errors. Changing one digit in either the latitude or longitude placed the data collection location on the proper stream. This range of acceptable errors was appropriate for our regional-scale assessments. Stations that did not meet these criteria or could not be located on the maps were removed from the files. For the nutrient data, we also removed stations that were obviously immediately downstream from lakes and reservoirs. We removed 17%, 18%, and 19% of the sites from the miscellaneous, metals, and nutrient retrievals, respectively, leaving 732, 821, and 1,111 stations. These data were loaded into the GIS as three separate files.

A set of dot maps was produced for the chemical values in Colorado streams, one map per chemical. A range of six colors from light yellow to dark brown represented low to high concentrations. Initially, the six class ranges were chosen by estimating where class breaks would produce groups of relatively even size. Colors for the classes were then projected onto a Colorado map that included ecoregion lines. The color classes were not chosen or shifted to emphasize ecoregional differences.

Plates 2 and 3 are representative examples of these dot maps, showing statewide patterns in median conductivity and Kjeldahl-nitrogen. Some general conclusions may be drawn from these maps. First, as might be expected, the Southern Rockies Ecoregion has distinctly different water chemistry from the other ecoregions in Colorado. A vast majority of the stations in this region are in the two lowest classes for conductivity (representative of ionic strength measures) and a smaller majority are in the two lowest classes for Kjeldahl-nitrogen (representative of nutrient measures). In the case of conductivity, it almost appears as though the ecoregion boundary was tailored to include as many light yellow dots as possible. On the east slope of the Southern Rockies, there is a downstream effect in the foothill areas in the two plains ecoregions, seen in the fringe of light yellow dots along the boundary in these eastern regions. The change in water type is more abrupt along the western boundary of the ecoregion. Many of the moderate concentration values in the Southern Rockies occur in the semi-desert shrublands subregion (Plate 1), the lowest elevation portion of the ecoregion.

Second, there do not appear to be strong regional differences among the nonmountainous regions for measures of ionic strength. But the two eastern plains ecoregions, the Western High Plains and Southwest Tablelands, appear to have more nutrient enriched streams than do the other nonmontane regions, and there is a definite downstream effect below cities. There is no ecoregional pattern for metals, only hotspots, which occur in the Rockies and near cities.

The distribution of ambient stream STORET stations sampled in the last decade is less than optimal for our purpose. The few stations in the eastern third of Colorado occur along large rivers. There is a relative lack of stations in the eastern, northern, and southern portions of the Rockies ecoregion and in the Arizona/New Mexico Plateau. Most stations appear along the western boundary, in the foothills and on the edge of the plains, of the two eastern regions, in a large oval area centered in the west-central Rockies, in portions of the Wyoming Basin, and over much of the Colorado Plateau. This distribution reflects an interest in problem areas near population centers and major resource developments (oil shale, coal, and metal mining). Thus the data can not be used for estimating minimally impacted conditions or for rigorously assessing the ecoregions and subregions.

The data base capabilities of the GIS were used to extract station median values by ecoregion for each chemical to produce boxplots. We expected the boxplots to confirm and quantify the information gained from the dot maps. In general this was true, but we gained other insights. For conductivity (Figure 3-10), the low values of the Southern Rockies were obvious, but similarity in values between the Wyoming Basin and the Arizona/New Mexico Plateau became more apparent. For some of the nutrients, the regional median values did not vary noticeably (Figure 3-11). The real regional differences occurred in the skewness that showed above the medians, that is, the increased range and number of stations impacted by nutrients in the two eastern ecoregions.

To gain further insight into regional water chemistry patterns, we ran a number of multivariate analyses, initially a principal components analysis (these analyses cannot be run if there are missing values). We chose to run the multivariate analyses on hardness, conductivity, and alkalinity for ionic strength. Among the nutrients, we chose nitrate/nitrite-nitrogen (for inorganic nitrogen), Kjeldahl-nitrogen (for organic nitrogen), and total phosphorus.

It is desirable to analyze data for which samples have been taken on several dates, to reduce the influence of possible outliers (we ignored seasonal variability for this study). We used the nutrients data file, with 1,111 stations containing various combinations of nutrient and ionic strength measures. In this file, 385 stations had all 3 ionic strength measures taken at least 3 times, but only 51 stations had all 3 nutrient measures taken 3 or more times, and only 38 stations had all 6 variables taken 3 or more times. Selecting stations that had all 6 parameters taken at least once gave us 71 stations.

We were concerned about the spatial distribution of these 71 stations, and about whether they had been heavily impacted by human activity. We mapped their locations and evaluated for impacts based on location and site description. We removed stations that were in or immediately

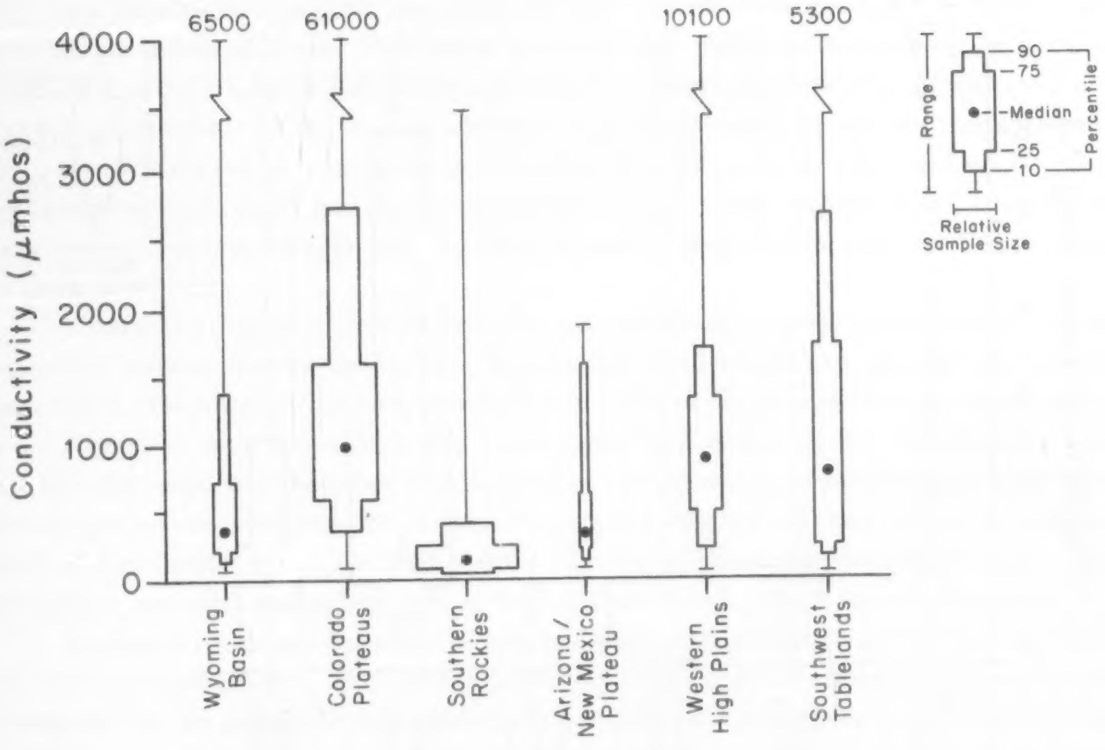

Figure 3-10. Regional patterns of conductivity in Colorado streams. Data are the same as for Plate 2.

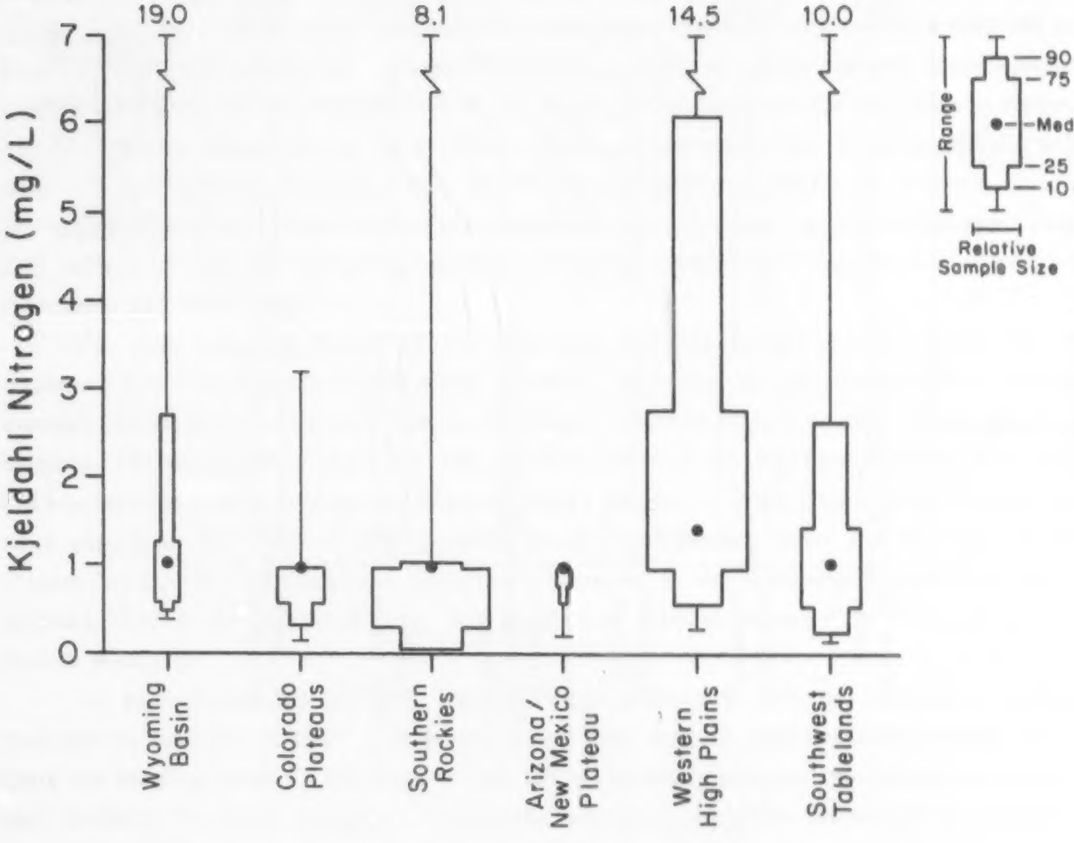

Figure 3-11. Regional patterns of Kjeldahl-nitrogen in Colorado streams. Data are the same as for Plate 3. Note that the regional median and 75th percentile values in the Colorado Plateaus, Southern Rockies, and Arizona/Mexico Plateau Ecoregions all equal approximately one.

downstream from cities, or that had extremely high nutrient levels. This left 48 stations for analysis. We also evaluated whether the contributing watershed for a station was representative of its ecoregion, or whether most of the waters came from another region. Based on this, we changed the ecoregion designation for eight stations, to more appropriately indicate the region of representation, and designated four others as boundary sites, with about 50% of the water coming from another region.

The correlations among the three ionic strength measures were high (> 0.87), and the first principal component accounted for 93.9% of the variability. The correlations among the nutrient measures were not as high. Kjeldahl-nitrogen correlated with the nitrate/nitrite-nitrogen ($r = 0.41$) and total phosphorus ($r = 0.55$), but total phosphorus and nitrate/nitrite-nitrogen were less correlated ($r = 0.17$). Thus the first principal component accounted for 59% of the variability and was weighted by Kjeldahl-nitrogen (0.66), total phosphorus (0.58), and nitrate/nitrite-nitrogen (0.48). These results are generally consistent with our work in Ohio (Larsen et al. 1988; Whittier et al. 1987) and Oregon (Whittier et al. 1988).

A scatterplot (Figure 3-12) of the first principal components (1st axes) of each analysis showed reasonable regional patterns; the Southern Rockies sites had low ionic strength and low nutrient enrichment. There was considerable overlap of site values in the Colorado Plateau and Wyoming Basin Ecoregions, with both having high ionic strength and moderately low to moderately high nutrient enrichment. The Southwest Tablelands (four sites) had moderate ionic strength and moderate to high nutrient concentrations. The Arizona/New Mexico Plateau (four sites) had low to moderate levels of both variable types. The single Western High Plains site had very high nutrients and ionic strength. A canonical discriminant analysis from the same data produced very similar results.

An alternative or supplement to the principal components analyses is to plot the site values of 2 or 3 chemicals together. Three-dimensional plots contain more information than two-variable scatterplots, but are more difficult to produce and interpret. Careful selection of variables will help avoid a proliferation of scatterplots. Conductivity should serve as a good surrogate for the ionic strength measures, due to their strong correlation. Total phosphorus and nitrate/nitrite-nitrogen were the least correlated nutrient pairs, and thus, should have less redundant information. Figure 3-13 presents three scatterplots of the log-transformed values of these three variables. The first plot shows regional patterns similar to the PCA plot (Figure 3-12). We expect this because total phosphorus loads most strongly on the nutrients PCA axis I. These plots show that total phosphorus helps differentiate the Arizona/New Mexico Plateau and the Southern Rockies Ecoregions, while nitrates/nitrites help differentiate the Wyoming Basin and the Colorado Plateaus Ecoregions. It is important to remember that, because these sites are not regional reference sites, the results can only *suggest* ecoregional differences.

We ran two additional multivariate analyses, discriminant analysis and stepwise discriminant analysis, on these data minus the single Western High Plains site (47 sites). Discriminant analysis identified the percentage of sites correctly classified by ecoregion, based on the six water chemistry

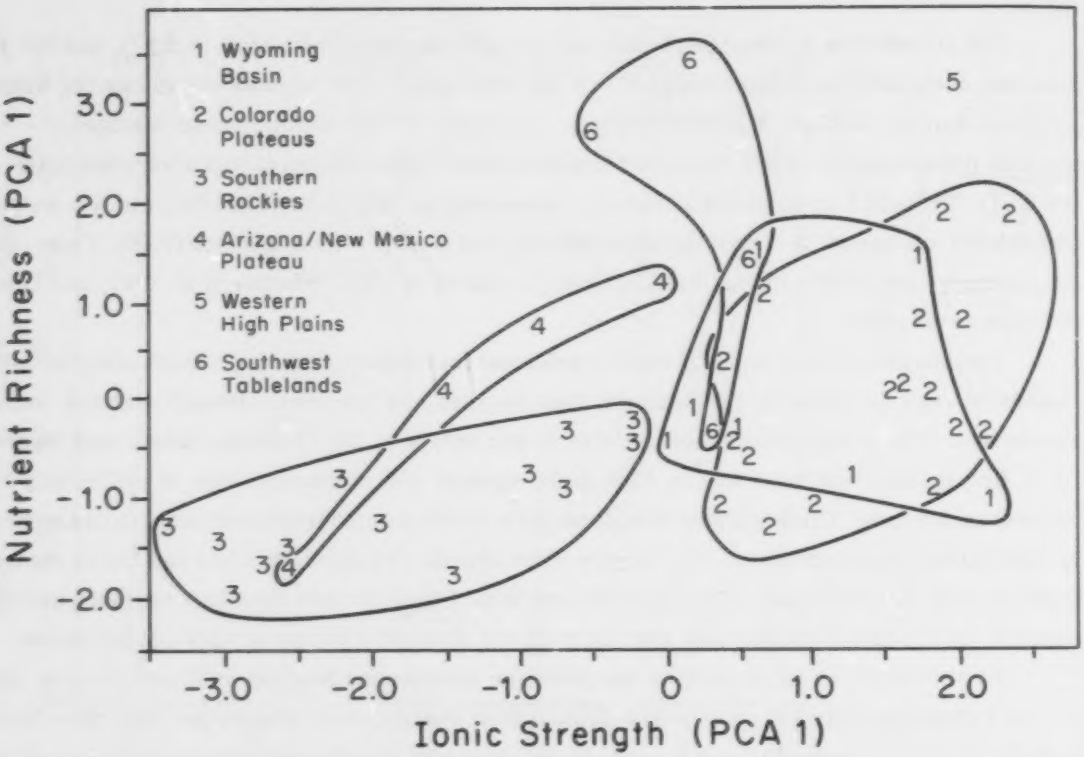

Figure 3-12. **Regional patterns in stream nutrient richness and ionic strength in Colorado streams, as indicated by principal component analysis axis I scores for each. Forty-eight sites were chosen, as described in Subsection 3.6.1.**

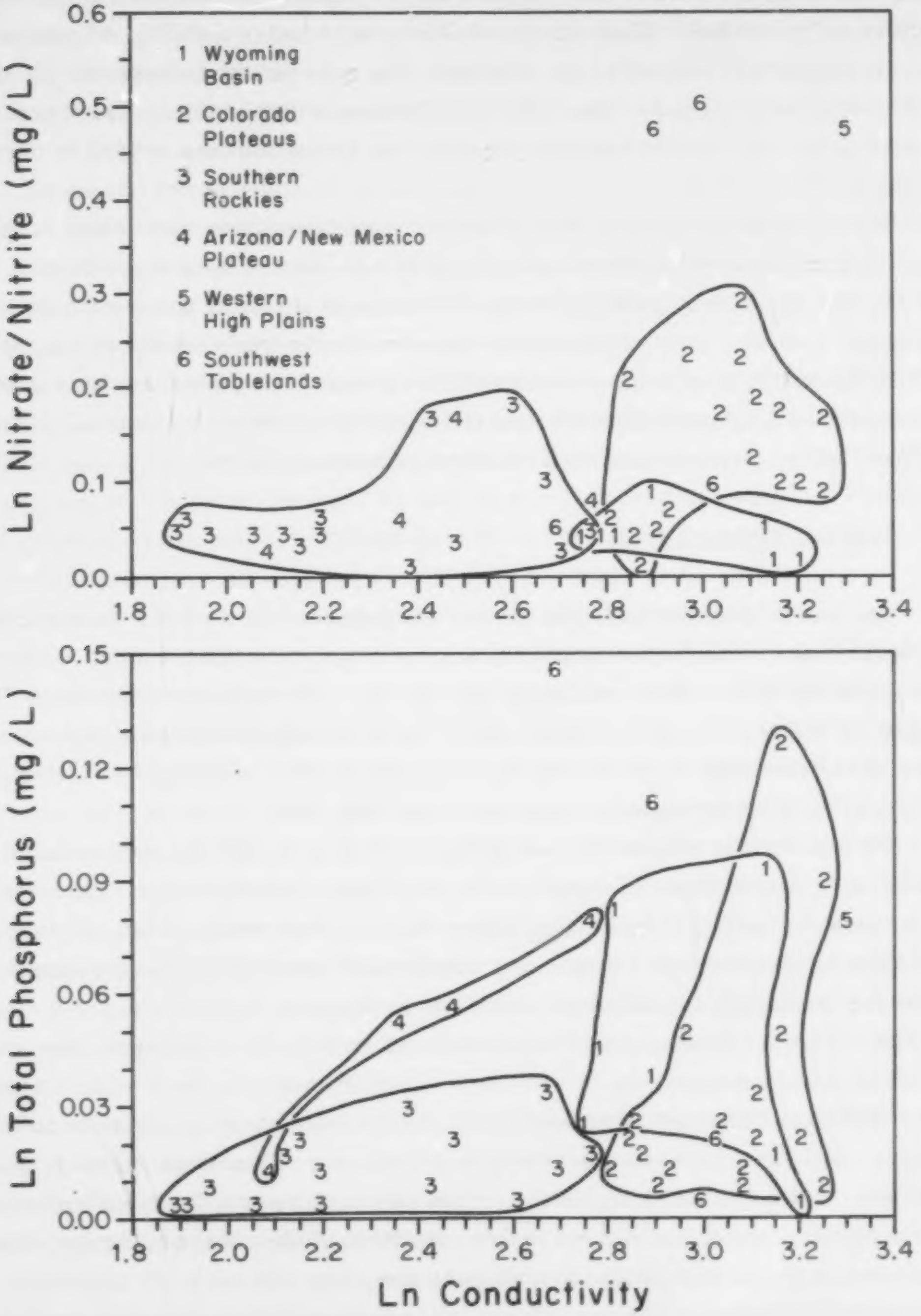

Figure 3-13. Regional patterns of total phosphorus, conductivity, and nitrate/nitrite-nitrogen in 48 Colorado stream sites. Sites are the same as in Figure 3-12. Values are Ln (x+1) transformed.

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values. The Arizona/New Mexico Plateau had only 50% correct classification, the other four regions ranged from 71.4 to 80%. Of the 12 misclassified sites, 4 had probabilities of membership in the correct ecoregion that differed by less than 10%. The stepwise discriminant analysis identified the variables most responsible for class differences (ecoregion membership). These were, in order of inclusion in the discriminant function, conductivity, nitrate/nitrite-nitrogen, hardness, and total phosphorus.

The overall results of these analyses are that spatial patterns in water chemistry for Colorado streams can be demonstrated at the regional level of resolution by using available data. This can be done despite very serious problems and shortcomings in the data, because the sheer volume of information overrides some of the noise. Thus, we can be fairly confident that streams in the Southern Rockies Ecoregion have considerably lower ionic strength and are less nutrient enriched than the other ecoregions in Colorado, and the two plains ecoregions in eastern Colorado generally have more highly enriched water than the other nonmontane regions.

3.6.2 Available Biological Data

The use of available biological data is hampered by most of the same problems of QC (appropriateness of sampling and reporting, and coverage [spatial distribution] of sampling) as the use of water chemistry data. In addition, there are no national data bases at present. This leads to the generic problems of lack of standardized sampling and, particularly, lack of standardized reporting and data base structure. Problems imposed by the condition of the data require that a strong level of effort be expended to extract useful information.

For any sizeable geographic area, biological data have probably been gathered by federal, regional, state, and local government agencies, by academic researchers, and, in areas of resource development, by private corporations. The problem is not usually a lack of data, but rather, difficulties in obtaining and restructuring the data into usable formats, in computerizing paper copies, and in assessing the quality of, and biases in, sampling.

The largest, centrally located or administered collections of biological data are with state wildlife or fisheries departments, or with major university museums. State wildlife department data tend to be biased toward selective sampling for and/or reporting of mostly game fish, and toward sampling mostly in areas where sport fisheries are expected. These departments generally will not have much, if any, nonfish biological data. University museum and/or academic departmental data may not be computerized and may not be freely available. If there are computerized data bases, they usually consist of one or two large *everything-by-everything* files.

Although considerable *nongame* biological research has been conducted, mostly by academic institutions, it is usually very difficult to assemble even a small minority of the data. The results reported in journal articles or books are almost always summaries. Thus, the precise sampling locations and dates, species occurrences and abundances, and concurrent data (e.g., physical habitat, water chemistry) are not provided. To acquire these data usually requires much time and energy.

Often the raw data no longer exist, are in paper form, or may not be released. In this subsection, we present examples of these problems, and of the difficulties in using data for purposes other than that for which they were intended, as they were encountered in the Colorado project.

The Colorado Division of Wildlife maintains a relatively large (approximately 3 megabytes) data base of about 4,700 stream reaches and associated fish and habitat data. This data base consists of two files, streams and fish, organized by stream reach rather than by collection. The streams file has 80 fields of mostly physical characteristics, spanning 645 columns. Although the Colorado Division of Wildlife supposedly provided us with a complete data base, several of the stream codes in the fish file did not match any in the streams file, so we do not know where these were collected. Also, a slight majority of the stream reaches reported *no fish*.

This data base had the usual data quality problems, such as incorrect locations, species codes, etc. In addition, several features of the data (structure, manner of coding, etc.) made it impossible to answer some questions at all or to assure good results. For example, there are four fields that record the percentage of a stream damaged by such factors as mining; an entry of *0* indicates no information gathered, rather than zero damage from that source. There are other instances of not being able to distinguish between *no data collected* and *data value equal to zero*.

Other problems arose from the organization of the data by stream reaches rather than by collection. If two or more collections were made on one reach, then at least two outcomes were possible. First, the most recent collection replaced the earlier, and historical information was lost. Second, the new collection was simply *added in* and species richness increased. This imposed strange results on the data; that is, the field that sometimes listed the relative abundances of the species at a site often added up to more than 100%. This happened when a new species was found and another, previously listed, species was not collected. The relative abundances of the previously found species remained in the data record and the currently collected species' relative abundances, which added up to 100%, were updated. It seemed as though multiple collections had been handled both ways, and it was not possible to know, without the original data, which method was used, or, in many cases, to know whether multiple collections had been made. Thus, at some sites, the abundance data had little value, and the presence/absence form of the data included more species than had been found at any one time.

There were other concerns, such as no indication of the purpose, quality, or completeness of the sampling. That is, did they collect and record all species or just certain game fish? Were they able to adequately sample all habitats for all species, or were there problems? Stream reaches (the default sites) ranged from a few tenths of a kilometer to over 150 kilometers. Sampling was supposed to have occurred near the lower end of the reach, but actual sampling locations were not recorded. All locations were given as township, range, and section, and thus GIS mapping of these data could not be done without locating the points by hand and determining approximate latitude and longitude coordinates. This was additionally complicated by the fact that Colorado has four separate land survey grids, as well as sizeable areas not included in any township system. Finally, a majority of the Colorado Division of Wildlife fish data were in the Southern Rockies Ecoregion, an area of great sports fishing potential. This area has been subject to a large fish stocking program, thus much of the fish data probably were greatly influenced by human intervention.

We acquired other biological data to supplement the Colorado Division of Wildlife data from a number of sources. The Colorado Division of Wildlife commissioned a number of studies of various drainages, often by graduate students at Colorado State University; Propst (1982) sampled 197 sites in the warmwater portion of the Platte River system, Loeffler et al. (1982) made 137 collections in the warmwater portion of the Arkansas River system, and Goettl (1982) evaluated the fisheries potential in the foothills and plains sections of the Arkansas, Cache la Poudre, and South Platte Rivers. The U.S. EPA commissioned Ruiter and Bishop to summarize existing knowledge of surface water systems in areas of potential oil shale development (tributaries and lower mainstems of the White and Colorado Rivers) (Ruiter and Bishop 1984a) and the Yampa River Basin (Ruiter and Bishop 1984b). Lewis and Saunders (1985) studied a 26-mile segment of the South Platte, beginning just downstream from Denver, for the Metropolitan Denver Sewage Disposal District. Saunders et al. (1982) summarized existing aquatic ecosystems information in northwest Colorado for the Bureau of Land Management, but deferred to other studies for fish data, and provided very general summaries of macroinvertebrate data. They shared misgivings similar to ours about using these data.

From the Propst, Goettl, and Loeffler reports, we have fairly good, site specific, fish data coverage of streams in the Western High Plains and the Southwest Tablelands Ecoregions. One option for analysis is a relatively intensive assessment of these two regions. For regional analysis to be effective, the following steps should be taken for each of the 350 sites:

a. Plot site locations on 1:250,000-scale U.S. Geological Survey topographic maps.
b. Estimate stream size class.
c. Evaluate the regional representativeness of the site, from a variety of maps, and the probable human impacts, from land use maps and point and nonpoint source data.
d. Computerize the species abundance and site data.
e. Select regional reference sites.

The regional reference data could be subjected to the kinds of analyses performed in the other state studies. For the data from these two regions alone, this process could conceivably consume more than half a labor-year.

Another option is a more qualitative assessment of regional fish distributions. Given the apparent low quality and large quantity of data statewide and the resources available for this project, we chose this option. Because the state is probably maintaining artificially high populations of introduced game species, particularly in the Southern Rockies, the trout species data do not represent natural regional patterns. Thus, we assessed the nontrout species data by mapping every reported occurrence of these fish. Species locations were marked with a dot on a 1:2,500,000-scale map of Colorado. At this scale, species locations are only rough approximations (errors of 8 km may occur), but will show regional-scale patterns.

Each data source presented its own limitations and difficulties for mapping. Propst's (1982) data were organized by species, rather than by collection, and included dot maps for all species he collected in the North and South Platte River systems in Colorado. For that part of the state we added dots to his maps from other data sources. However, it became clear that some, but not all, of his data were in the Colorado Division of Wildlife data base, and some of his locations had been sampled by others. It would have been very time consuming to check every species at every site for duplication in the Colorado Division of Wildlife data. Thus, some species occurrences may have been mapped twice.

The Loeffler et al. (1982) report contained three maps of sample locations in the Arkansas River drainage, one for each sampling year. Using these maps, we transferred their data onto our state maps. However, some sites were sampled more than once, so some species occurrences may be double-mapped. In addition, their sampling was aimed at locating threatened species, and so may be biased toward locations with uncommon fish. Although the Colorado Division of Wildlife paid for the report, these data are not in their data base.

The Ruiter and Bishop reports (1984a, 1984b), on the surface waters of the oil shale region and the Yampa River basin, are summaries of other studies. These contain a fair amount of fish species information not included in the Colorado Division of Wildlife data base. However, only approximate locational information was available. For some streams, Ruiter and Bishop simply listed the species reported anywhere within the basin. For others, they mapped the sampling locations for each study and provided a table of all species reported by each study, but not the location for each species. Sometimes fish distributions were presented as a table of occurrences within a defined reach of the stream. Thus, mapping their information either over- or under-reports species occurrences.

For the remainder of the state, consisting of the east slope and the central and southern west slope of the Rockies, the Republican River basin, and the southwest/southcentral portions of the state, we have only the Colorado Division of Wildlife data. Outside of the Rockies, there is very limited coverage. Thus, we can realistically make only a very general, qualitative assessment of regional fish patterns.

We added the ecoregion boundaries on our fish data maps and counted the dots for each species in each region, producing a list of all nontrout species reported per ecoregion and their relative frequency of occurrence. To visualize these patterns, the species' site counts were converted to fractions of the count for the most widespread species in that region. The *relative frequencies of occurrence* were plotted as histograms to produce a species signature (Figure 3-14). This figure is only a rough qualitative representation of the relative commonness, by region, of nontrout species. The Wyoming Basin and the Arizona/New Mexico Plateau regions had very few sites.

Interpreting regional patterns in fish distributions is complicated by the strong river basin effect. For example, many species are found on only one side of the continental divide. In Colorado, there is a moderate spatial correspondence between river drainages and nonmontane ecoregions, so that a fair amount of the regional differences in fish distributions can also be explained by basins.

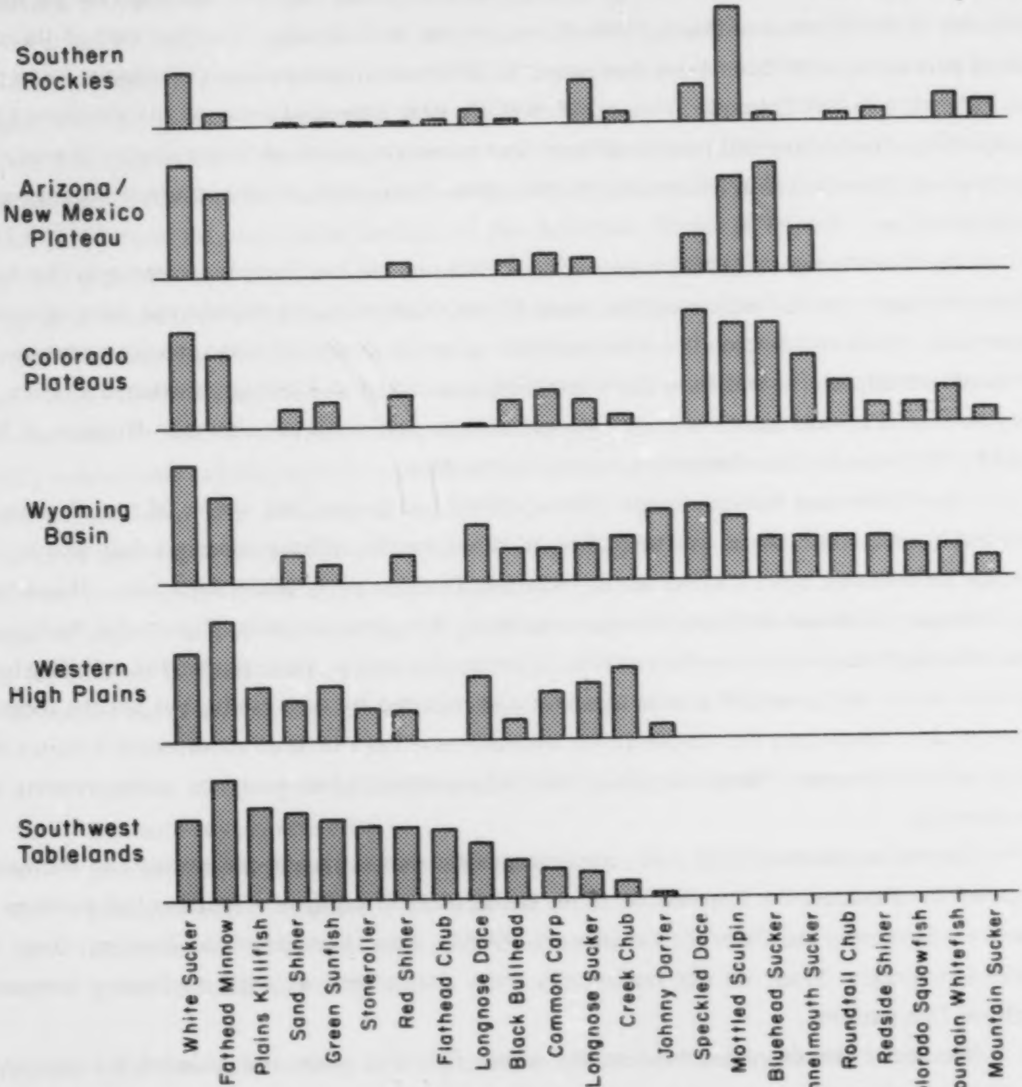

Figure 3-14. Regional relative frequency of occurrence of fish in Colorado streams. For each species, the height of the bar is relative to the frequency of occurrence of the most widespread (most commonly sampled) nontrout species in that region. Counts of sample sites were determined as described in Subsection 3.6.2. These species signatures are very qualitative.

The white sucker and fathead minnow are nearly ubiquitous in Colorado, except in the Southern Rockies Ecoregion. The two eastern regions have similar species makeup. The flathead chub was found only in the Arkansas River system, and thus, only in the Southwestern Tablelands Ecoregion. The sand shiner, red shiner, stoneroller, and plains killifish were more common in the Southwestern Tablelands than in the Western High Plains Ecoregion. The creek chub and longnose sucker were more common in the Western High Plains, as were some large river species uncommon in Colorado, such as river carpsucker, suckermouth minnow, gizzard shad, and orangespotted sunfish. The latter three species occurred in the Arkansas River near where it flows into the Western High Plains Ecoregion; however this apparent regional effect is most likely due to water release from the John Martin Reservoir, as the river dries up completely in western Kansas (D.L. Miller, pers. comm.).

The fish species composition of the Wyoming Basin Ecoregion is transitional between that of the eastern plains ecoregions and the nonmontane regions west of the divide. In Colorado, a portion of the Wyoming Basin Ecoregion is in the North Platte River drainage and the remainder is in the Colorado River drainage. The johnny darter is most common in this region, but only east of the divide. Most of the remaining species characteristic of the Colorado portion of this ecoregion occur only on the west side.

The Colorado River system, and thus the Colorado Plateaus Ecoregion, is characterized by western large river fish such as the six species on the right side of Figure 3-14, and by speckled dace and mottled sculpin in the smaller streams. The mountain sucker and mountain whitefish were found only in the northwest quarter of the state. The Arizona/New Mexico Plateau occurs on both sides of the divide and had species characteristic of both drainage systems. We had very few samples from this region, particularly in the Rio Grande drainage. The Southern Rockies Ecoregion was dominated by various introduced trout species. Most of the nontrout species in this region occurred only on the west side, except for white sucker and longnose sucker.

We mapped the Colorado Division of Wildlife data for cutthroat trout, the only Colorado native trout, and found the expected large number of sites in the Southern Rockies Ecoregion, about four times that of the most common nontrout species. Data for the nonmountainous regions showed that many streams maintain enough *mountainous* character to support trout for some distance into nonmountainous regions. A similar pattern occurs in Oregon (Hughes and Gammon 1987; Hughes et al. 1987). Also, the Colorado Division of Wildlife appeared to have sampled a relatively large number of cutthroat sites in the Colorado Plateaus, Wyoming Basin, and Arizona/New Mexico Plateau Ecoregions, which are not generally considered *trout* regions. In fact, these data imply that trout are the most widespread fish in the Colorado Plateaus Ecoregion. This tends to confirm our suspicions about the game fish bias in sampling and reporting.

We also mapped the locations of streams with no fish reported, to identify spatial patterns of streams not supporting fish. Most of these were listed as gulches, implying that they were short streams with very little or no water much of the year, but subject to random torrential flows that eliminate fish. There were no apparent spatial patterns in these data.

3.7 SECTION SUMMARY

In this section we have presented an overview of some of the issues and methods involved in using environmental data to evaluate regional characteristics, as well as some examples of results from these evaluations. Quantification of the range of data values representing various regional characteristics can be accomplished by collecting and analyzing environmental data at selected sites, including minimally impacted reference sites, or by judicious use of existing data. The next section illustrates how the results of this process, within an ecoregional framework, can be used for resource management and regulation.

SECTION 4

APPLICATIONS OF A REGIONAL APPROACH

4.1 INTRODUCTION

Most of the development of the ecoregional assessment process was stimulated by a need within the regulatory framework of the National Environmental Policy Act (Public Law 91-190, 1 Jan. 1970) and, more recently, the Clean Water Act, as amended by the Water Quality Act (WQA) (Public Law 92-500, 18 Oct. 72), and numerous amendments, to assess existing and attainable water quality. Stimulus for development of this framework came from several state water quality agencies that wanted to improve their water quality assessment and management procedures. So, most of the development and evaluation were conducted in cooperation with state water quality agencies. Accordingly, our discussions reflect a preponderance of state applications within the context of meeting the WQA mandates. Several common themes occur throughout the examples of state studies: the characterization of least impacted, regional reference sites to define ecological attainability in different regions and identify resources that may need protection, the use of ecoregions as an organizational framework for assessing and interpreting environmental data, and the use of ecoregions as statistical strata for the development of sound sampling designs to estimate the status of spatially distributed ecological resources.

This section has been organized into three main parts. Section 4.2 describes how this regional framework has been used by several states to meet some of the requirements of the U.S. EPA's Water Quality Standards Regulation, which describes how specific parts of the WQA are to be addressed. Section 4.3 summarizes examples in which this regional framework has been used for monitoring, assessment, and reporting, as required by WQA sections 305(b), 314 (clean lakes), and 319 (nonpoint sources), and as a basis for state and national sampling designs (e.g., National Acidic Precipitation Assessment Program lake and stream surveys [Linthurst et al. 1986; Landers et al. 1987; Kaufmann et al. 1988]). Section 4.4 offers a general description of various potential applications. Whereas Sections 4.2 and 4.3 show how the process has been incorporated into national or state regulatory and assessment programs, Section 4.4 describes some directions in which we think this approach has additional utility, although they have not yet been tried. Some of these possible applications are under consideration by various state agencies; others have not been explored in any depth. We offer the ideas to stimulate interest and discussion; further discussion, development, and testing will be required prior to their use.

4.2 WATER QUALITY STANDARDS

The WQA clearly articulates the goal of restoring and maintaining the ecological integrity of the nation's waters. This goal is stated throughout the document, including *...restore and maintain* *the chemical, physical, and biological integrity of the nation's waters, ...assure protection and propagation of a balanced indigenous population of fish, shellfish, and wildlife, ...develop and publish criteria on the effects of pollutants on biological community diversity, productivity, and stability, including information on factors affecting ....rates of organic and inorganic sedimentation for varying types of receiving waters.* Section 303(c) of the Act requires that water quality standards are to protect the public health and welfare, enhance the quality of the water, and serve the purposes of the Act *by taking into consideration their use and value for public water supplies, protection and propagation of fish and wildlife, recreation, agricultural and industrial water supplies, and navigation.*

The U.S. EPA's Water Quality Standards Regulation (WQSR) (40 CFR Part 13) addresses the WQA requirements concerning protection and restoration of *physical, chemical and biological integrity of the nation's waters.* The regulation describes the standards in three parts: (1) designated uses, (2) criteria (numeric or narrative) that, if achieved, protect designated uses, and (3) antidegradation. *Designated uses* are the goals for specific water bodies and include aquatic life (e.g., fishing), recreation (e.g., swimming and aesthetics), or water supply (domestic, agricultural, industrial). Subcategories may also be used; for example, aquatic life uses might be subdivided into warmwater and coldwater, or further subdivided into warmwater habitat, exceptional warmwater habitat, or limited resource.

In the past, EPA focused on limiting pollutant discharges based on the best available technology. However, now that many of the more dramatic water quality and human health problems have been resolved, attention is being focused on the remaining, often more subtle and complex, pollution problems, including nonpoint source pollution. This shift is reflected in a focus on the quality of receiving waters and on the variety of tools required to achieve water quality goals for specific water bodies.

An important aspect for achieving the goals of the WQA is the ability to specify ecologically achievable goals. Some states have recognized the need to accommodate regionally varying achievable quality and the need to define aquatic life uses more explicitly through biological criteria. In some cases, an ecoregional framework has been used to set chemical and biological criteria to supplement traditional methods. Case studies from Arkansas and Ohio are summarized in Subsections 4.2.1 and 4.2.2 to illustrate how chemical and/or biological criteria can be developed using the regional framework. A synopsis of their sampling design and frequency of sampling is included in Appendix B. In Minnesota, a regional framework was used to organize and interpret existing stream and lake data, primarily for assessing trophic condition and attainable trophic quality. A discussion of Minnesota's efforts is presented in Section 4.3.

4.2.1 Arkansas

The Arkansas Department of Pollution Control and Ecology is charged with carrying out the mandates of the WQA and WQSR in Arkansas. The Department adopted an ecoregional framework to identify natural differences in existing and achievable chemical quality among streams in different parts of the state. The Department also wanted to acknowledge regional differences in stream biotic assemblages. But a formal process was needed to identify areas where similar chemical and biological quality could be expected. This was especially critical with regard to dissolved oxygen, because in some areas it appeared that the national or statewide criteria could not reasonably be achieved even in streams not impacted by point and nonpoint sources of pollution; in late summer, these streams of low dissolved oxygen supported diverse, viable fish communities. In other cases, the Department thought criteria were not stringent enough to protect aquatic life uses. The results of sampling and characterizing reference streams within an ecoregion framework supported these observations in a more determinant way.

Thus, the Arkansas Department of Pollution Control and Ecology developed and adopted regionally specific numeric criteria for selected water quality attributes, based on observations at regional reference streams. These included temperature, turbidity, and dissolved oxygen. For dissolved oxygen, the criteria were further stratified into values for streams of different watershed sizes within each region. In some cases, particular rivers received specific criteria. Table 4-1 and Figure 4-1 present a summary of these regionally specific criteria.

The Department has also used the regional framework to establish narrative biological goals for streams. The state's *Fisheries* use designation addresses the WQA requirement for the protection and propagation of fish, shellfish, and other forms of aquatic life. This use is subdivided into three categories: (1) trout, (2) lakes and reservoirs, and (3) streams. For streams, the Department describes the characteristics of regional fish assemblages that are to be achieved to meet this use designation, based on the regional reference stream collections. Thus, for particular streams, assessment of use attainment is based partially on a comparison of the resident assemblage with the regional reference assemblage (Table 4-2).

4.2.2 Ohio

Ohio's Water Quality Standards are designed to provide a basis for protecting and restoring surface waters for a variety of uses, including the protection and propagation of aquatic life. Aquatic life use designations established by the Ohio Environmental Protection Agency include: warmwater habitat, modified warmwater habitat (proposed), exceptional warmwater habitat, coldwater habitat, seasonal salmonid habitat, and limited resource waters. These designations have been qualitatively defined in ecological terms, and chemical criteria, either quantitative or narrative, have been established for each. In addition, numerical biological criteria (biocriteria) have been defined for three of the classes (warmwater habitat, modified warmwater habitat, and exceptional warmwater habitat), based on instream fish and macroinvertebrate assemblages. The Ohio EPA used the ecoregional framework to develop a reference set of data to establish biocriteria.

Table 4-1. Regional Temperature and Turbidity Criteria for Arkansas Streams (Arkansas Department of Pollution Control and Ecology 1988)

Ecoregion	Temperature[1] (°C)	Turbidity[2] (NTU)
Ozark Highlands	29	10
Boston Mountains	31	10
Arkansas Valley	31	21
Ouachita Mountains	30	10
South Central Plains	30	21
Mississippi Alluvial Plain	30	45
Channel-altered Mississippi Alluvial Plain	32	75

[1] Maximum allowable temperatures from human-induced causes.

[2] Maximum allowable turbidity from human-induced causes.

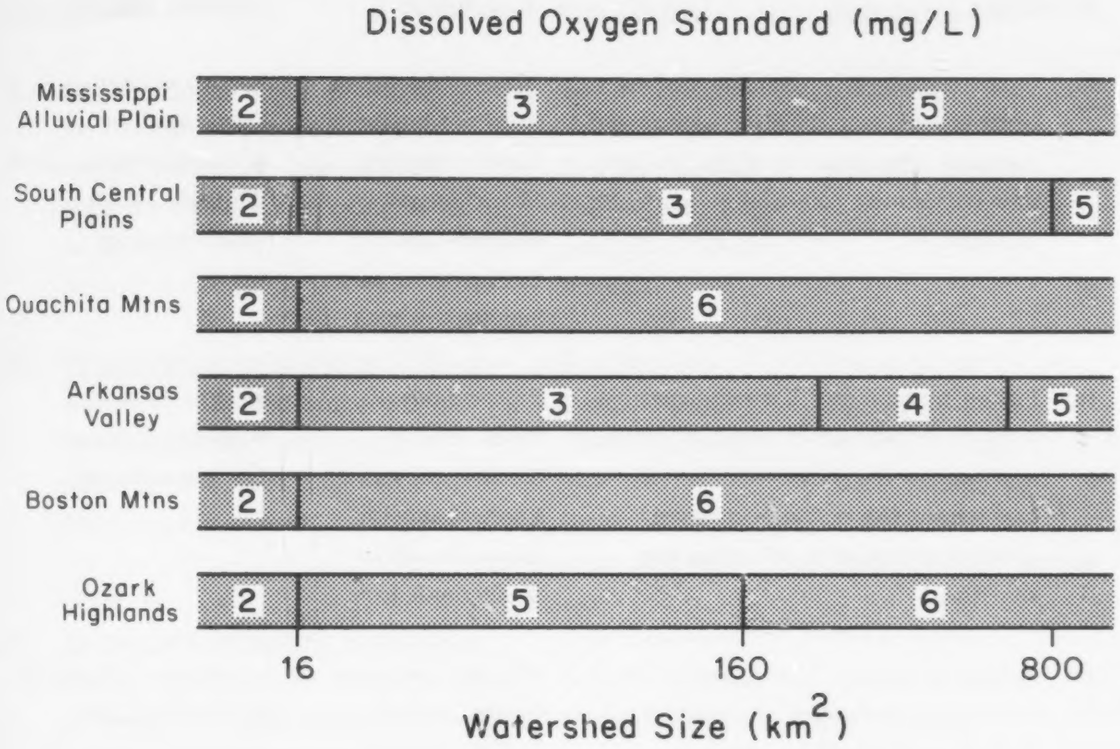

Figure 4-1. Dissolved oxygen standards for Arkansas streams during the critical season (late summer low flow). This figure illustrates the relationships among oxygen criteria, stream size (based on watershed size), and ecoregions in Arkansas. Bennett et al. (1987) and Giese et al. (1987) should be consulted for details regarding these standards.

Table 4-2. Summary of Arkansas' Descriptions of Fish Communities in Reference Streams (Arkansas Department of Pollution Control and Ecology 1988). In all ecoregions, streams are to support diverse communities of indigenous or adapted species of fish and other forms of aquatic life.

Ecoregion	Key Species[1]	Indicator Species[2]
(a) Ozark Highlands - Characterized by a preponderance of sensitive species and normally dominated by a diverse minnow community followed by sunfishes and darters.	Duskystripe shiner Northern hogsucker Slender madtom "Rock" basses Rainbow and/or Orangethroat darters Smallmouth bass	Banded sculpin Ozark madtom Southern redbelly dace Whitetail shiner Ozark minnow
(b) Boston Mountains - Characterized by a major proportion of sensitive species; a diverse, often darter-dominated community exists, but with nearly equal proportions of minnows and sunfishes.	Bigeye shiner Black redhorse Slender madtom Longear sunfish Greenside darter Smallmouth bass	Shadow bass Wedgespot shiner Longnose darter
(c) Arkansas Valley - Characterized by a substantial proportion of sensitive species; a sunfish- and minnow-dominated community exists, but with substantial proportions of darters and catfishes (particularly madtoms).	Bluntnose minnow Golden redhorse Yellow bullhead Longear sunfish Redfin darter Spotted bass	Orangespotted sunfish Blackside darter Madtoms

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[1] Key species: normally the dominant species within important groups such as families or trophic levels.

[2] Indicator species: a species readily associated with a specific type of ecosystem; is not necessarily dominant.

(Continued)

Table 4-2. Summary of Arkansas' Descriptions of Fish Communities in Reference Streams (Arkansas Department of Pollution Control and Ecology 1988). In all ecoregions, streams are to support diverse communities of indigenous or adapted species of fish and other forms of aquatic life. (Continued)

Ecoregion	Key Species[1]	Indicator Species[2]
(d) Ouachita Mountains - Characterized by a major proportion of sensitive species; a minnow- and sunfish-dominated community exists, followed by darters.	Bigeye shiner Northern hogsucker Freckled madtom Longear sunfish Orangebelly darter Smallmouth bass	Shadow bass Gravel chub Northern studfish
(e) Typical Southcentral Plains - Characterized by a limited proportion of sensitive species; sunfishes are distinctly dominant, followed by darters and minnows.	Redfin shiner Spotted sucker Yellow bullhead Flier Slough darter Grass pickerel	Pirate perch Warmouth Spotted sunfish Dusky darter Creek chubsucker Banded pygmy sunfish
(f) Springwater-influenced Southcentral Plains - Characterized by a substantial proportion of sensitive species; sunfishes normally dominate the community, followed by darters and minnows.	Redfin shiner Blacktail redhorse Freckled madtom Longear sunfish Creole darter Grass pickerel	Pirate perch Golden redhorse Spotted bass Scaly sand darter Striped shiner Banded pygmy sunfish
(g) Least-altered Mississippi Alluvial Plains - Characterized by an insignificant proportion of sensitive species; sunfishes are distinctly dominant, followed by minnows.	Ribbon shiner Smallmouth buffalo Yellow bullhead Bluegill Bluntnose darter	Pugnose minnow Mosquitofish Pirate perch Tadpole madtom Banded pygmy sunfish

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[1] Key species: normally the dominant species within important groups such as families or trophic levels.

[2] Indicator species: a species readily associated with a specific type of ecosystem; is not necessarily dominant.

(Continued)

Table 4-2. Summary of Arkansas' Descriptions of Fish Communities in Reference Streams (Arkansas Department of Pollution Control and Ecology 1988). In all ecoregions, streams are to support diverse communities of indigenous or adapted species of fish and other forms of aquatic life. (Continued)

Ecoregion	Key Species[1]	Indicator Species[2]
(h) Channel-altered Mississippi Alluvial Plain - Characterized by an absence of sensitive species; sunfishes and minnows dominate the community, followed by catfishes.	Blacktail shiner Drum Common carp Channel catfish Green sunfish Spotted gar	Mosquitofish Gizzard shad Emerald shiner

[1] Key species: normally the dominant species within important groups such as families or trophic levels.

[2] Indicator species: a species readily associated with a specific type of ecosystem; is not necessarily dominant.

For the development of biological criteria, the Ohio EPA relied on the composition and relative abundance of macroinvertebrate and fish assemblages. Indices of ecological health were calculated by combining species abundance data by site with trophic guild, pollution tolerance, and ecological information about the species. Three indices were used; two of these, the Index of Biotic Integrity (IBI) and the modified Index of Well-Being (IWB), are based on fish assemblages; the third, the Invertebrate Community Index (ICI), was derived from macroinvertebrate assemblages. The IBI was modified from Karr's Index of Biotic Integrity (Karr et al. 1986), and the IWB was a modification of Gammon's work (Gammon 1976, 1980; Gammon et al. 1981). The Ohio EPA applied the ecological principles used in the IBI and IWB to develop the macroinvertebrate ICI (Ohio Environmental Protection Agency 1987b). The regional reference data were used to establish expected values of each index for each region and for each aquatic life use for which biocriteria were established.

Ecoregional criteria were established for the warmwater habitat class at the 25th percentile value of the reference site data for each ecoregion for each index. Criteria for the exceptional warmwater habitat class were established at the 75th percentile, based on a statewide assessment of data from reference streams; these latter criteria were not established on a regional basis. In addition, modified warmwater habitat criteria were established for some streams whose physical habitats had been altered, particularly by channelization, impoundments, or nonacidic mine drainage, to such an extent that the expected Warmwater Habitat use could not be realistically attained, but these streams could support some semblance of a Warmwater Habitat community. Two biocriteria were established for this class, one for the sites in the Huron/Erie Lake Plain, and one for the sites in the remainder of the state. The criteria were the 25th percentile values of representative sites in each area.

Aquatic life use attainment in Ohio streams is assessed primarily on the basis of biological monitoring; in other words, the ability of a waterbody to achieve the biocriteria. The significance of any observation of non-attainment is based on the magnitude of departure from the regional criterion (e.g., within four IBI units of the ecoregion criterion) and the distance downstream over which the departure is sustained. Generally, attainment of warmwater habitat and modified warmwater habitat is achieved when all three of the biocriteria (IBI, ICI, and IWB) have been met. If only one or two index values are met, the use is partially attained. Non-attainment is based on failure of all indices to meet the applicable criteria. An example of regional biological criteria is given in Table 4-3. Assessing use attainment is discussed in more detail in Subsection 4.3.2.

4.2.3 Minnesota

The Minnesota Pollution Control Agency has focused efforts on the protection and restoration of lake water quality because lakes are a prime recreational resource in that state. The Agency has used an ecoregional framework to summarize existing lake chemistry data in order to derive appropriate achievable regional goals and criteria for lake quality. The framework has proven

Table 4-3. Biocriteria for streams in the Proposed Ohio Water Quality Standards Regulations (Ohio Environmental Protection Agency 1987b). This example is based on Karr's Index of Biotic Integrity, and is an illustration of the way the Ohio EPA established biocriteria.

Index of Biotic Integrity (Fish)	Modified Warmwater Habitat			Warmwater Habitat
	Channel Mod.	Mine Affected	Impounded	
A. Wading Sites[1]				
Huron/Erie Lake Plain	22			32
Interior Plateau	28			36
Erie/Ontario Lake Plain	28			38
Western Allegheny Plateau	28	26		42
Eastern Corn Belt Plains	28			40
B. Boat Sites[1]				
Huron/Erie Lake Plain	22		24	34
Interior Plateau	26		30	38
Erie/Ontario Lake Plain	26		30	36
Western Allegheny Plateau	26	24	30	38
Eastern Corn Belt Plains	26		30	42

[1] Sampling methods descriptions are found in the Ohio EPA Manual of Surveillance Methods and Quality Assurance Practices (Ohio Environmental Protection Agency, Division of Wastewater Pollution Control, 1983).

(Continued)

Table 4-3. Biocriteria for streams in the Proposed Ohio Water Quality Standards Regulations (Ohio Environmental Protection Agency 1987b). This example is based on Karr's Index of Biotic Integrity, and is an illustration of the way the Ohio EPA established biocriteria. (Continued)

Index of Biotic Integrity (Fish)	Modified Warmwater Habitat			Warmwater Habitat
	Channel Mod.	Mine Affected	Impounded	
C. Headwaters Sites[1]				
Huron/Erie Lake Plain	22			32
Interior Plateau	26			40
Erie/Ontario Lake Plain	26			40
Western Allegheny Plateau	26	26		40
Eastern Corn Belt Plains	26			40

[1] Sampling methods descriptions are found in the Ohio EPA Manual of Surveillance Methods and Quality Assurance Practices (Ohio Environmental Protection Agency, Division of Wastewater Pollution Control, 1983).

valuable in organizing and interpreting landscape and water quality data. The key concern has been lake phosphorus and lake attributes that are influenced by elevated levels of phosphorus. A summary of the results of the Agency's effort, including water quality goals and criteria, is provided in Subsection 4.3.3.

4.3 WATER BODY MONITORING, ASSESSMENT, AND REPORTING

An ecoregional framework has also been effectively used to support the U.S. EPA's efforts to assess the status and extent of water quality problems. Specifically, the framework has been used for (1) designing survey programs, (2) conducting direct assessments of aquatic life use attainment, and of the status and extent of water quality problems, and (3) synthesizing and interpreting water quality monitoring data, as required by Sections 305(b), 314, and 319 of the WQA.

4.3.1 Monitoring Design

The ecoregional framework is useful in two broad areas of monitoring program design. The first area is the monitoring of water resources to determine the attainable or achievable quality in a particular region. Examples are discussed in Section 4.2 and are not repeated here. The second area pertains to developing unbiased estimates of the status of water quality resources with known precision (such as the fraction of lakes or streams in a particular area that meet a particular environmental criterion).

Traditionally, water quality agencies have relied on an enumerative process to quantify the extent of water quality problems and water body use impairment. The goal of this process is to identify and list water bodies that are impaired. An estimate of status and extent of impairment in an area is obtained by totaling the extent (lengths for streams, area for lakes and reservoirs) of the impaired systems, or by mapping the spatial distribution of impaired systems. As presently practiced, this method lacks statistical rigor; that is, the status of the resources of interest cannot be specified with known confidence or precision.

An alternate, statistically sound, survey design has been developed as part of the mandate to assess, with known precision, the status of lakes and streams, relative to sensitivity to acidic deposition, and to estimate the number that are already acidic. This design adopts an inferential process that relies on estimating population characteristics by sampling subsets of the population. Specifying the population of interest and randomly sampling (systematic random, or stratified systematic random) that population is the basis for making statistically sound inferences about status and extent with known precision.

Although a purely random process for site selection can be used in survey designs, stratification of the population of interest into subpopulations of greater homogeneity can increase the precision of estimates for the same sampling resources. For estimating the quality of resources that exhibit spatial patterns (e.g., water quality), a geographic stratification into areas of greater homogeneity efficiently focuses sampling. The use of a geographically stratified random sampling design formed the basis of assessment of surface water sensitivity to acidic deposition nationwide. A brief description of the sampling design for one part of the country is detailed below to illustrate the process.

The National Lake Survey was designed by the U.S. EPA to assess the chemical status of lakes in areas of low alkalinity in the United States, in order to estimate the number and percentage of lakes sensitive to acidic deposition or already exhibiting acidic conditions (Linthurst et al. 1986; Landers et al. 1987). The sampling design was constructed so that results could be extrapolated to the population of lakes in the areas of interest. Several levels of geographic stratification were used to establish sampling strata from which a random sample of lakes could be drawn. The population was defined as those lakes in areas (regions) of the United States where a majority of lakes have alkalinities of less than 400 μeq/L. The first level of stratification consisted of regions having relative homogeneity in lake type and in physiographic characteristics affecting lake type, such as continental glaciation, alpine glaciation, and karst topography, and included portions of the Upper Midwest, Northeast, and Southeast United States. The second level of stratification was established by identifying areas (subregions) within each region that were relatively homogeneous in combinations of factors affecting differences in lake quality, such as lake size and type, physiography, vegetation, climate, and soils. Five subregions were delineated in the Northeast, four in the Upper Midwest, and two in the Southeast United States. This level of regionalization was used to ensure that representative samples were obtained from each environmentally distinct area. The third level of stratification consisted of alkalinity map classes, within each subregion, derived from regional alkalinity maps (Omernik and Griffith 1986; Omernik and Kinney 1985) and based on the expected range of dominant surface water alkalinity values.

Within each of these strata, the population of lakes was limited to those appearing on 1:250,000-scale U.S. Geological Survey topographic maps. The lakes were first enumerated and labelled, then a systematic sample (with a random start) was selected for field sampling to insure that each lake within the population had an equal probability of selection. This selection was refined by eliminating *nontarget*[6] lakes.

The regional/subregional classification, combined with the systematic random sampling of lakes, allowed population estimates to be made with known precision by characterizing sample lakes. This sampling design has the potential for addressing many other questions about the status and extent of aquatic resource quality. For example, it can be used to estimate the number or percentage of lakes in a region that are eutrophic or that exceed certain phosphorus levels, or to estimate the percentage of streams having aquatic life uses that are impaired or attained.

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[6] Nontarget lakes include lakes in urban or industrial areas, lakes less than the specified 4 ha minimum, and lakes inaccurately represented on the 1:250,000-scale topographic maps (e.g., no lake actually present on the ground, or the lake is actually flowing water, a swamp, or a bay/estuary).

Some researchers believe that a systematic grid is a more appropriate sampling scheme for certain environmental studies. Preliminary regionalization of the interest area can help to distinguish the degree of environmental variability within and among regions and, thus, the appropriate coarseness for a sampling grid. Sites will then be located close enough together to represent all important environmental conditions in the data set.

4.3.2 Assessment of Aquatic Life Use Attainment

Comparing existing chemical conditions with chemical criteria is an indirect way of assessing aquatic life use attainment, important for understanding how potential impairment might be caused by suspected chemical pollution. Aquatic life use attainment can also be assessed directly. One way is to establish quantitative biocriteria against which existing conditions can be compared. A second way is to compare existing conditions with those at several reference sites. Traditionally, this latter method is the upstream/downstream analysis of suspected impairment caused by point source discharges. However, this approach can be broadened to include reference watersheds or reference sites in similar watersheds. Results from many of these comparisons could be used as a basis for establishing biocriteria. A third way is to compare ambient conditions against the predictions of well-verified mathematical models. All these methods can provide quantitative statements about the status of a water body and the extent to which an aquatic life use is impaired. In the examples that follow, a regional framework has been used to facilitate the application of the first and second methods for direct assessment of aquatic life use attainment.

4.3.2.1 Ohio--

As described earlier, the Ohio EPA used an ecoregional framework to establish biocriteria that differed among the ecoregions in that state. These regional biocriteria have been used in the assessment of use impairment as part of the Ohio EPA's ongoing monitoring and assessment program. An example of one such study demonstrates the application of the process for site specific assessments.

A warmwater habitat stream, located in the Erie/Ontario Lake Plain Ecoregion, receives point source discharges (Figure 4-2; Ohio Environmental Protection Agency 1987b). Each graph in Figure 4-2 indicates various levels of attainment of each index. Chemical pollution sources are indicated at the top of the figure; the X-axis indicates river kilometers. The lines trace the longitudinal profile of the index values along the stream. In this case, above the sources of chemical pollution, the stream attains its regional Warmwater Habitat biocriteria (i.e., 40 for the IBI, 8.0 for the IWB, and 36 for the ICI). Below the discharges, impairment is seen in each index, followed by movement toward recovery. Note that the indices respond slightly differently. The IBI and the IWB indicate a steady trend toward recovery, whereas the ICI indicates a trend toward recovery followed by possible further degradation.

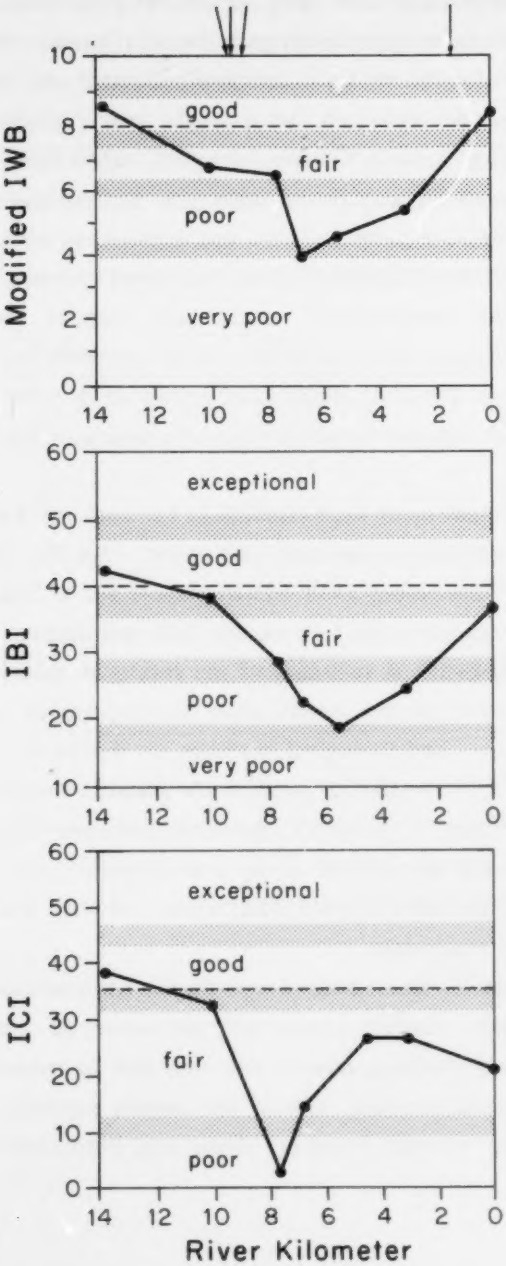

Figure 4-2. Illustration of how the Ohio Environmental Protection Agency (1987b) uses biocriteria to interpret the significance of an environmental impact. Chemical pollution sources are indicated by arrows at the top of the figure. The stream is designated as warmwater habitat and is located in the Erie/Ontario Lake Plain Ecoregion; applicable biocriteria are indicated by the dashed horizontal lines.

The Ohio EPA also assessed how well aquatic life use impairments based on biocriteria compared with those based on chemical criteria for 431 stream segments (Ohio Environmental Protection Agency, Division of Water Quality Monitoring and Assessment 1988). Ambient chemistry from grab samples collected for a single year (usually the summer months) were compared with the chemical criteria to assess chemical impairment. The biotic integrity indices were generated for the same streams in the same year and compared with the biocriteria values established for each of the ecoregions to assess use impairment directly. Used in the comparison were temperature, conventional chemicals (e.g., dissolved oxygen, ammonia, chlorine, nitrate-nitrogen, nitrite-nitrogen), conventional metals (e.g., copper, cadmium, zinc, lead, nickel, chromium), and other inorganic chemicals known to be problems in certain areas of the state (e.g., arsenic). Criteria are from the Ohio Water Quality Standards (Ohio Administration Code 3745-1, 1987). Impairment was assessed based on the combination of the frequency and magnitude of criteria exceedence.

Three levels of use impairment were established for both the chemical and biological criteria: full attainment, partial attainment, and non-attainment. See the Ohio EPA, Division of Water Quality Monitoring and Assessment 1988 305(b) Report for a description of the chemical and biological assessment procedures used to assign full attainment, partial attainment, or non-attainment to a stream segment. A summary of the results of these assessments is given in Table 4-4. The diagonal elements of the matrix show the percentage of cases in which there was agreement between chemical and biological methods; an overall agreement of 46% is indicated. The other elements of the matrix indicate the cases in which assessments conflict. For example, in 35% of the cases, a chemical assessment indicated full attainment but a biological assessment indicated partial attainment or non-attainment. In nearly half of these cases, impairments were due to habitat or flow modifications, or silt. These kinds of impairments are not detected by chemical assessment.

The Ohio EPA's statewide assessment of aquatic life use attainment in streams was previously based on chemical surveys. Recent reports rely on results of biosurveys. The difference in reported stream kilometers attaining aquatic life uses can be substantial, as the above example indicates; based on chemical surveys, 52% of the stream segments would be assessed as fully attaining aquatic life uses, whereas based on biosurveys, only 23% have full attainment.

4.3.2.2 Montana--

Hughes (1985) used regional reference sites to examine the impacts of sediments and heavy metals on the biota of streams in the metal mining district of southwestern Montana. Because appropriate upstream reference sites were lacking, the experimental design incorporated the selection of reference watersheds similar to the impaired watersheds in regional characteristics, such as land-surface form, climate, soil, vegetation, and land use. Three impaired sites were chosen for assessment, and three reference sites were selected for comparison with each of the

Table 4-4. The Ohio Environmental Protection Agency's (Ohio Environmental Protection Agency, Division of Water Quality Monitoring and Assessment 1988) Comparison of Percent of Stream Segments Attaining Aquatic Life Uses, Based on Biosurvey and In-stream Chemical Data

Chemical Attainment	Biosurvey Attainment			
	Full	Partial	Non-	Total
Full	17	18	17	52
Partial	2	1	6	9
Non-	4	6	28	39
Total	23	25	52	

Rows indicate full attainment, partial attainment, or non-attainment based on in-stream chemistry; columns indicate attainment based on biosurveys (n = 431 stream segments). For example, based on a chemical assessment, 52% of the segments fully attained aquatic life uses; only 23% achieved full use attainment based on biosurveys. The two types of assessment agreed on full attainment in 17% of the cases.

impaired sites. Reference and impaired streams were sampled once during the late summer to characterize and compare aquatic life (fishes and macroinvertebrates), water quality, and physical habitat. The results indicated the extent to which the streams were impaired. Conclusions were that chemical and physical habitats were disrupted at the impacted sites, and that the mere presence of trout in impaired sites was an insufficient measure of ecological integrity for these sites. That is, even though trout were present at the impaired sites, there were significant differences among the biotic assemblages (fish and macroinvertebrates) relative to reference sites, indicating that the impaired segments did not achieve the attainable quality for this area.

4.3.2.3 Colorado--

Fausch and Schrader (1987) modified Karr's Index of Biotic Integrity (IBI) to assess the biotic integrity along various sections of the Cache la Poudre River, Big Thompson River, and St. Vrain Creek in northeastern Colorado (western part of the Western High Plains Ecoregion). They sampled these streams from 1980 to 1985, collecting in the urban areas, in the transition zone, and downstream into the plains. They calibrated the index for streams in this portion of the South Platte River Basin by examining data on fish collections obtained in other surveys. These surveys included collections at sites that were minimally impaired compared to the rest of the basin.

Fausch and Schrader concluded that IBI scores in the stream reaches they sampled were within the fair to poor range, with a general decline in the downstream direction. They also concluded that point source discharges at Ft. Collins had no detectable effect on the measured biotic integrity in the receiving reaches of the Cache la Poudre River. They noted that habitat alterations, especially channelization, markedly reduced biotic integrity.

Fausch and Schrader did not conduct their study specifically to determine whether aquatic life uses were attained. Nonetheless, their results can be discussed within that framework. The IBI scale includes categories that are good and excellent. Because the IBI was regionally calibrated, these categories may represent attainable conditions. The scores in the good to excellent range could be defined as biological criteria that specify the attainment of a warmwater fishery use, as Ohio EPA has done. Biotic integrity of all reaches in the Fausch-Schrader study fell into the fair to poor range on this scale, indicating possible widespread use impairment. More severe impairment occurred in the reaches affected by physical habitat modifications.

4.3.3 Synthesis and Reporting of Water Quality Monitoring Data

Minnesota has used an ecoregion framework for more assessment applications than any other state. The Minnesota Pollution Control Agency has found the ecoregional framework to be a convenient and effective way to organize, present, and interpret lake and stream water quality information. This framework has been used in several congressionally mandated reports (e.g., as required by WQA Sections 305(b), 314 [clean lakes], and 319 [nonpoint sources]) and also as the organizational basis for several reports and presentations made to the public at scientific meetings. A number of publications should be consulted for greater detail (Heiskary 1989; Heiskary and Walker, Jr. 1988; Heiskary and Wilson 1988; Heiskary et al. 1987; Minnesota Pollution Control Agency 1986a, 1986b, 1986c, 1988a, 1988b, 1989; Wilson 1989; Wilson and Walker, Jr. 1989). The Agency adopted the ecoregional boundaries as outlined by Omernik (1987a) to summarize large amounts of existing lake and stream chemistry data. As the data were summarized and interpreted, this framework became useful for deriving regionally achievable lake quality goals and criteria. Equally important has been its use for communicating with the public about water quality status, achievable goals, and identification of high quality resources needing protection. The framework has also proven valuable in organizing and interpreting landscape and water quality data. The key concern has been lake phosphorus and lake attributes that are influenced by elevated levels of phosphorus. To demonstrate the wide variety of applications, we have organized a synthesis of the Minnesota Pollution Control Agency's efforts along the topics of (1) ecoregion characterization, (2) water body characterization, (3) water quality characterization and attainable quality, (4) lake phosphorus modeling, and (5) implications for management.

4.3.3.1 Ecoregion Characterization--

The Minnesota Pollution Control Agency combined several existing state data bases and developed more detailed descriptions of the seven ecoregions occurring in Minnesota than were originally provided by Omernik and Gallant (1988), in order to aid in data interpretation and environmental management. One data base summarized land characteristics and was organized by the Land Management Information Center. Aerial photography coverage for 1968-1969, augmented by other sources, was used to characterize the 16-ha parcels of land included in this data base. The Land Management Information Center also aggregated these data by *minor watersheds*. The Minnesota Pollution Control Agency summarized the minor watershed data within each ecoregion to characterize the ecoregion as a whole, as well as describe those parts typical of each region and those parts transitional in nature. Precipitation data from the Minnesota Department of Natural Resources and flow data from the U.S. Geological Survey were also used. Another data source summarized land use changes that had occurred since the survey done by the Land Management Information Center. The ecoregions could be characterized by data that included land use, water orientation, water quantity, precipitation, soil texture and hydrologic group, slope, and population characteristics.

Water orientation refers to whether or not a 16-ha parcel of land borders a water body. The category *no surface water* indicates that no surface water resources are associated with that parcel; *stream oriented* indicates that a stream crosses or borders a parcel and *lake oriented* refers to a parcel that includes a lake shoreline. The *water* category includes parcels that are primarily lake or wetland.

Major differences were seen in some of these characteristics across Minnesota's ecoregions. The greatest differences occurred between regions to the north (the Northern Lakes and Forests and Northern Minnesota Wetlands Ecoregions) and regions to the south (the Western Corn Belt Plains and Northern Glaciated Plains Ecoregions), as summarized in Figure 4-3.

4.3.3.2 Water Body Characterization--

The distribution of number, type, and quality of lakes differs among ecoregions. Of the seven ecoregions occurring in Minnesota, only the Northern Lakes and Forests, North Central Hardwood Forests, Western Corn Belt Plains, and Northern Glaciated Plains should be considered as *lake regions*, as 98% of the state's lakes occur in these four ecoregions. The density and characteristics of the lakes vary regionally. In the Northern Lakes and Forests Ecoregion, lakes are generally small, deep, and stratified, whereas in the Northern Glaciated Plains they are large, shallow, and unstratified (Figures 4-4 and 4-5).

4.3.3.3 Water Quality Characterization--

Data collected from streams and lakes as part of the Minnesota Pollution Control Agency's ongoing water quality assessment program have been analyzed using an ecoregional framework. Lake quality data were obtained over the period from 1977 to 1987 and focus primarily on water quality variables of importance to lake trophic state (e.g., phosphorus, Secchi disk transparency, and chlorophyll *a*). For streams, a broad array of chemical attributes was assessed from 1965 to 1987 as part of the Agency's routine ambient stream monitoring network. Although the ecoregional framework has been used to organize and interpret both lake and stream data, the design of the monitoring program was not initially based on the framework, and the streams and lakes do not represent reference conditions. As a result of the regional assessments and a desire to identify attainable water quality, both the stream and lake programs have recently shifted emphases to explicitly identify and sample least impacted water bodies.

The lake monitoring program incorporates the Minnesota Pollution Control Agency's routine efforts, those of other agencies, and a public lake monitoring effort. These endeavors have provided a data base of more than 1400 lakes. A second monitoring effort focuses on a reference set of lakes representative of the ecoregions and least impacted by point and nonpoint sources of pollution. Several of these lakes have been monitored for several years to assess natural yearly variability. This monitoring effort is limited to lakes in the four lake ecoregions. An ecoregional framework is being used to summarize and present the data collected from these monitoring programs and interpret the data relative to management needs.

Figure 4-6 displays the regional differences in lake quality based on the reference data. As expected, and consistent with the patterns seen for streams, the ecoregional framework accounts for a substantial part of the variation. Some of the remaining within-region variation can be

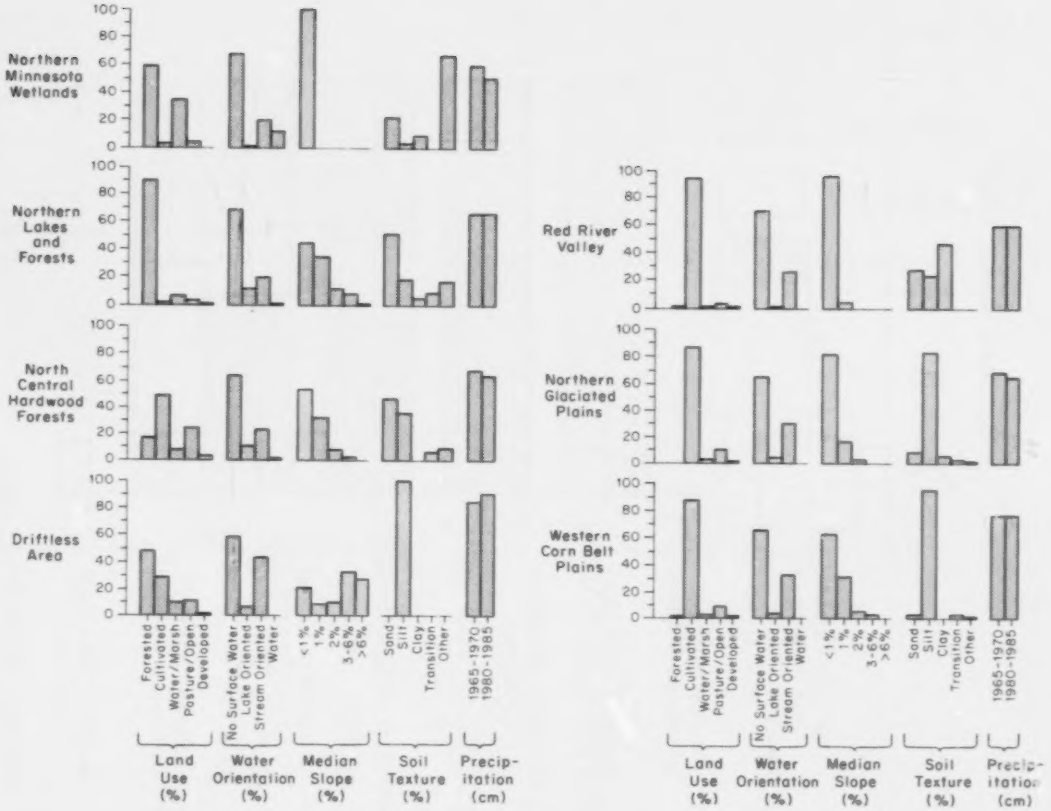

Figure 4-3. Summary of characteristics in regionally representative areas in Minnesota ecoregions. Precipitation is summarized by entire region (Minnesota Pollution Control Agency 1989).

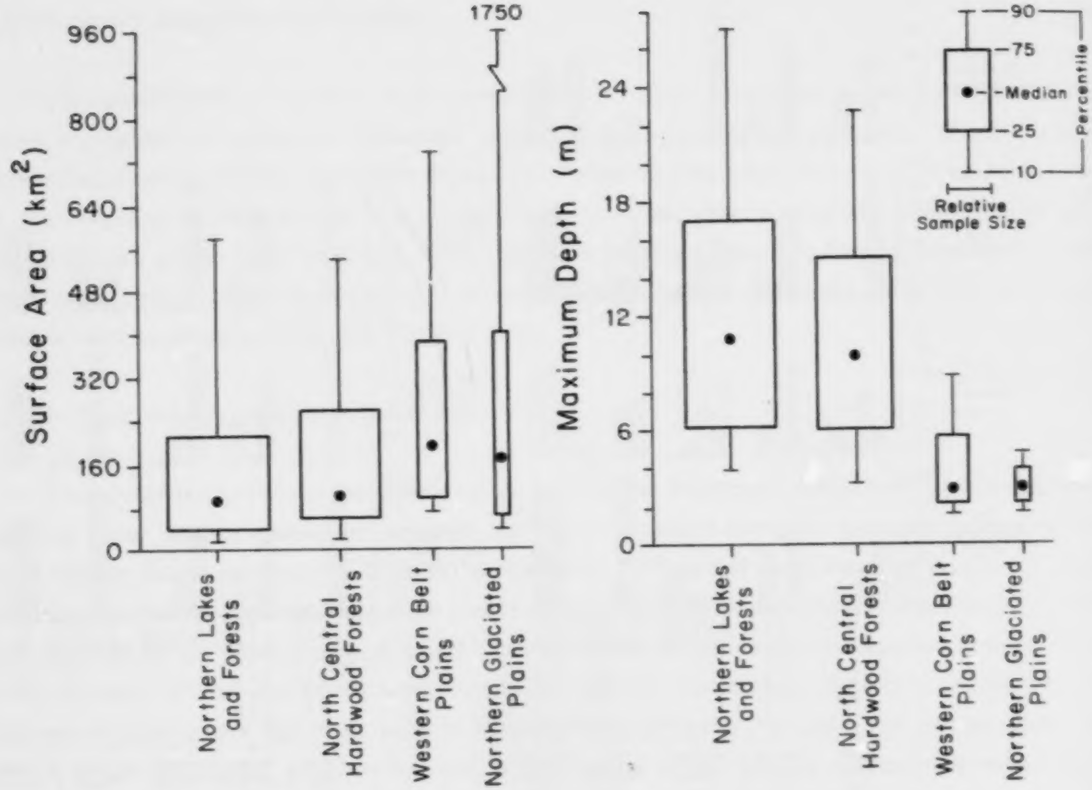

Figure 4-4. **Boxplots of regional differences in surface area and maximum depth for Minnesota lakes (adapted from Heiskary and Wilson 1988).**

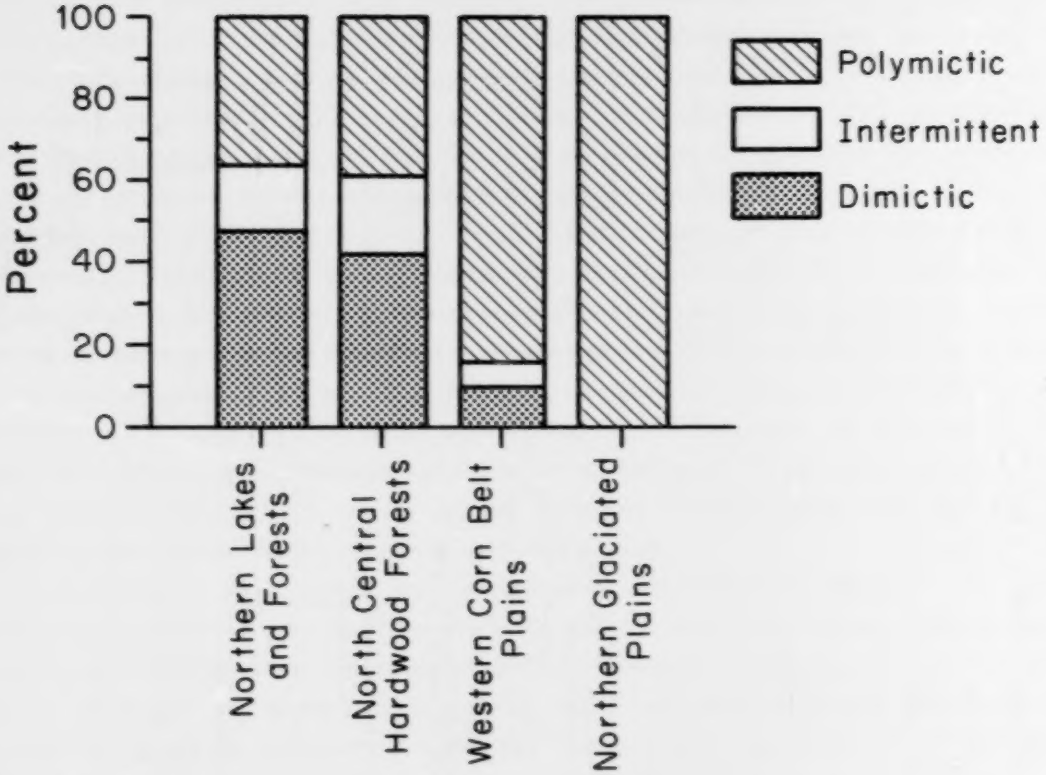

Figure 4-5. Percent composition of lake mixing types for Minnesota ecoregions (adapted from Heiskary and Wilson 1988).

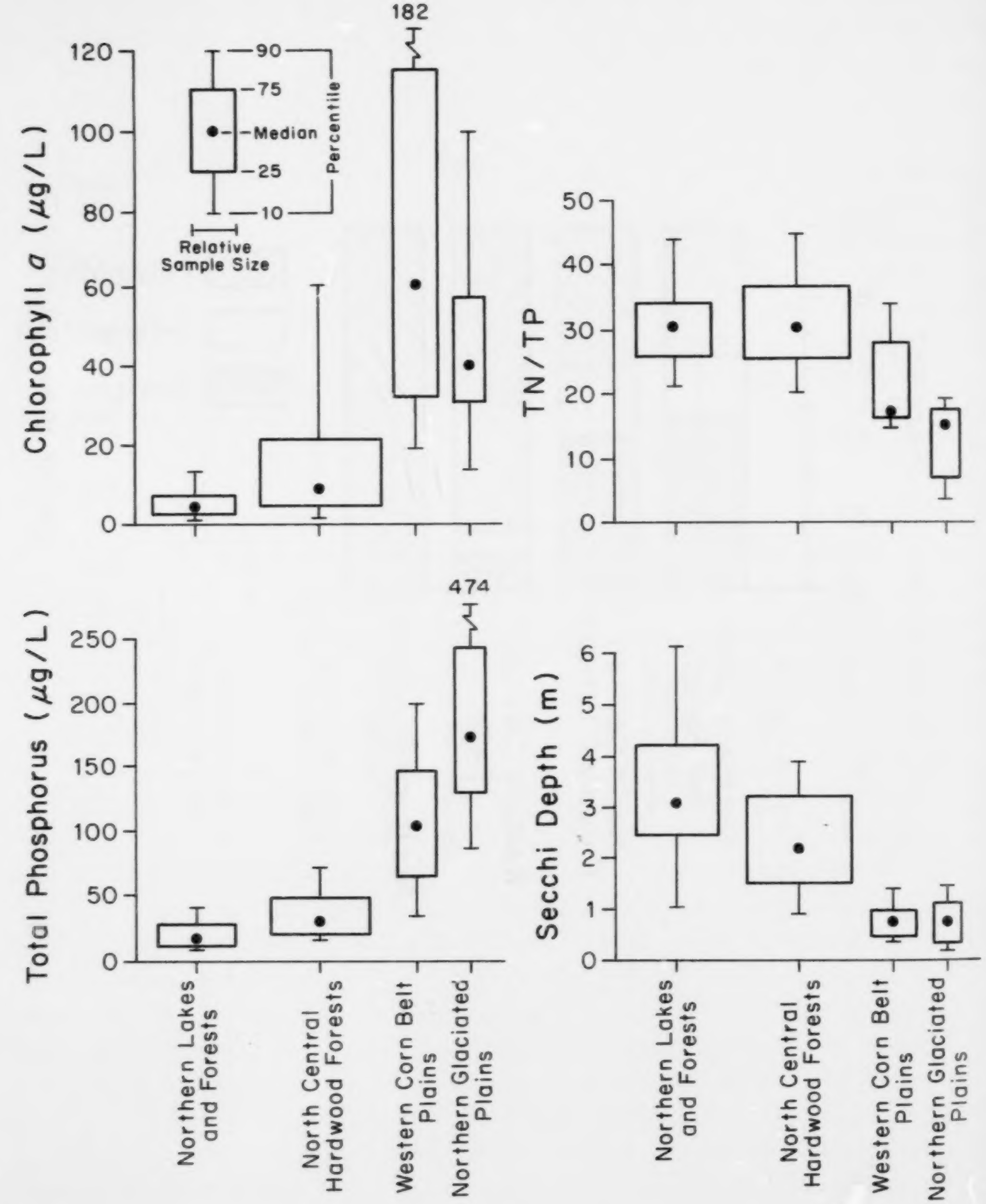

Figure 4-6. Regional differences in lake water quality in Minnesota based on a survey of least impacted lakes (Heiskary 1989).

accounted for spatially, by creating subregions (Omernik et al. 1988). In addition, the data base can be subdivided by categories to investigate other possible sources of variation, such as lake depth, mixing regime, lake type (seepage vs. drainage), or other factors. Figure 4-7 shows an example of variation in lake total phosphorus within ecoregions associated with fishery ecological class.

The Minnesota Pollution Control Agency also related citizen *user perceptions* of lake quality to the chemical measurements. User perceptions were assessed on a scale of from one to five through a questionnaire that ranked quality by lake physical appearance, ranging from *crystal clear* to *dense algal blooms*, and recreational suitability, ranging from *beautiful, could not be nicer* to *no recreation possible because of algae levels.* Water quality measurements for total phosphorus, Secchi disk transparency, and chlorophyll *a* were obtained at the same time the questionnaire survey was conducted. Results summarized the frequency distributions that related questionnaire scores with water quality characteristics. Figure 4-8 shows one such comparison for Secchi disk transparency. Significant regional differences were seen in user perception of impairment. For example, water bodies perceived as *no swimming* or *high or severe algae* in the Northern Lakes and Forests Ecoregion have transparencies ranging from one to two meters. This compares with typical transparencies of 2.5 to 4.2 m found in reference lakes (Figure 4-6) in this region. However, in the Western Corn Belt Plains Ecoregion, the perception of the same level of impairment occurred at transparencies of 0.3 to 0.9 m, where typical transparencies are 0.5 to 1 m at reference lakes. Water quality that is acceptable in the Western Corn Belt Plains is apparently unacceptable in the Northern Lakes and Forests.

The results of these citizen surveys and their relationship to measured lake quality characteristics have been incorporated by the Minnesota Pollution Control Agency into the process of setting goals and criteria and assessing attainment of designated lake uses. For instance, a case can be made that use impairment occurs at higher transparencies (lower phosphorus and chlorophyll *a* levels) in the Northern Lakes and Forests than in the Western Corn Belt Plains. Thus, management goals should reflect these regional differences.

For analyzing existing stream data, the Agency established criteria for the selection of sites to be included in the regional assessment. These criteria were: (1) at least four years of data must be available, (2) data must have been collected monthly for at least nine months, and (3) streams must be reasonably representative of their ecoregions. As a result, 149 stream monitoring stations were selected. Stream temperature, pH, conductivity, total suspended solids, turbidity, nitrate/nitrite nitrogen, ammonia, total phosphorus, 5-day BOD, and fecal coliform were analyzed for three different time intervals: 1965-1970, 1980-1985, and the entire 20-year period. Analysis of stream data was divided into two phases. All streams meeting the three criteria were used in one phase. These streams were impacted to varying degrees, reflecting the range of human influences present in each region. In the other phase of analysis, a subset of less impacted streams (relative to the others) were selected to estimate attainable quality and conditions for each ecoregion. This first cut at attainable quality can be refined as the monitoring program is modified to include streams that are selected specifically with minimal impact as a criterion.

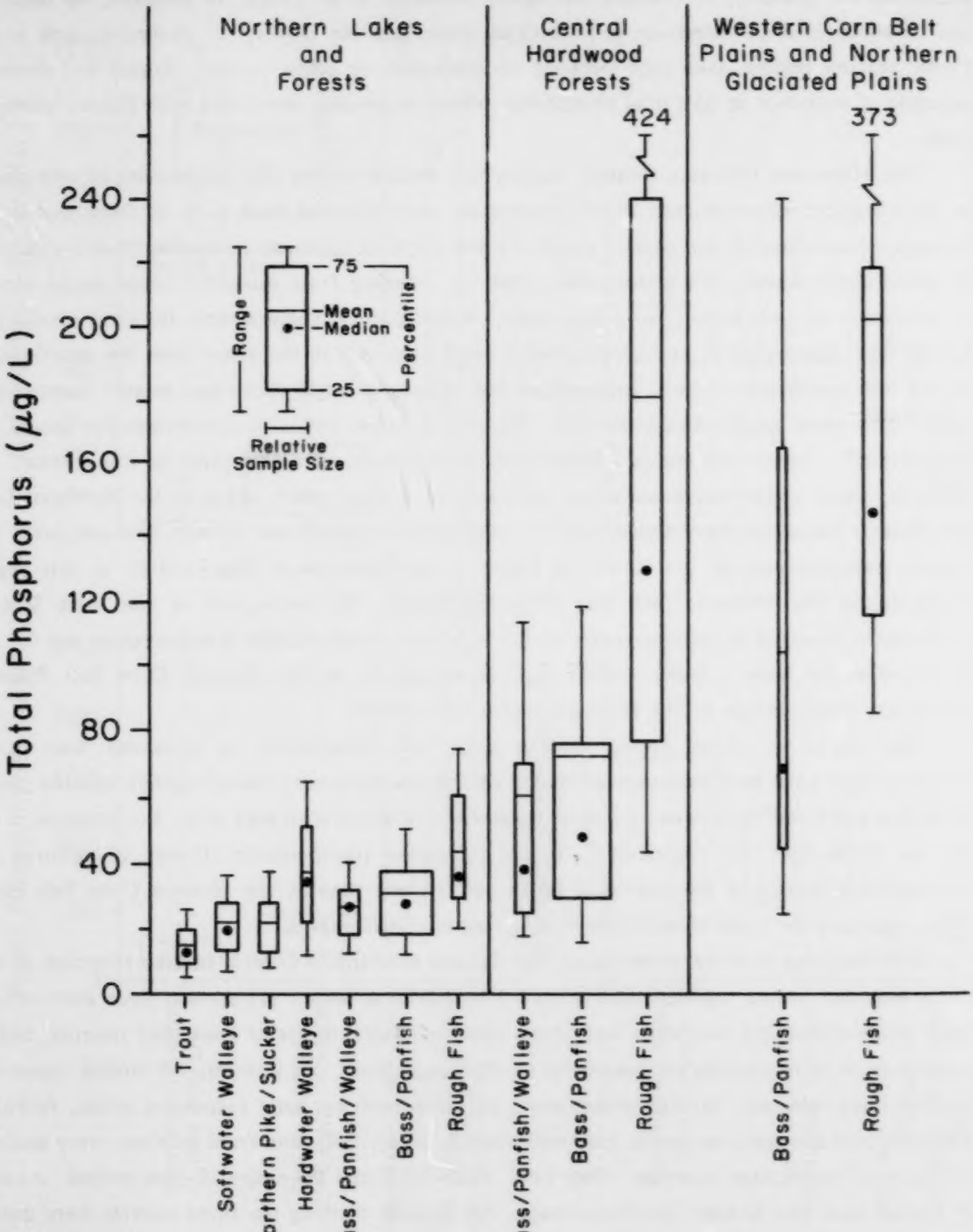

Figure 4-7. **Boxplots of total phosphorus concentrations by fishery ecological class in Minnesota ecoregions (Heiskary and Wilson 1988).**

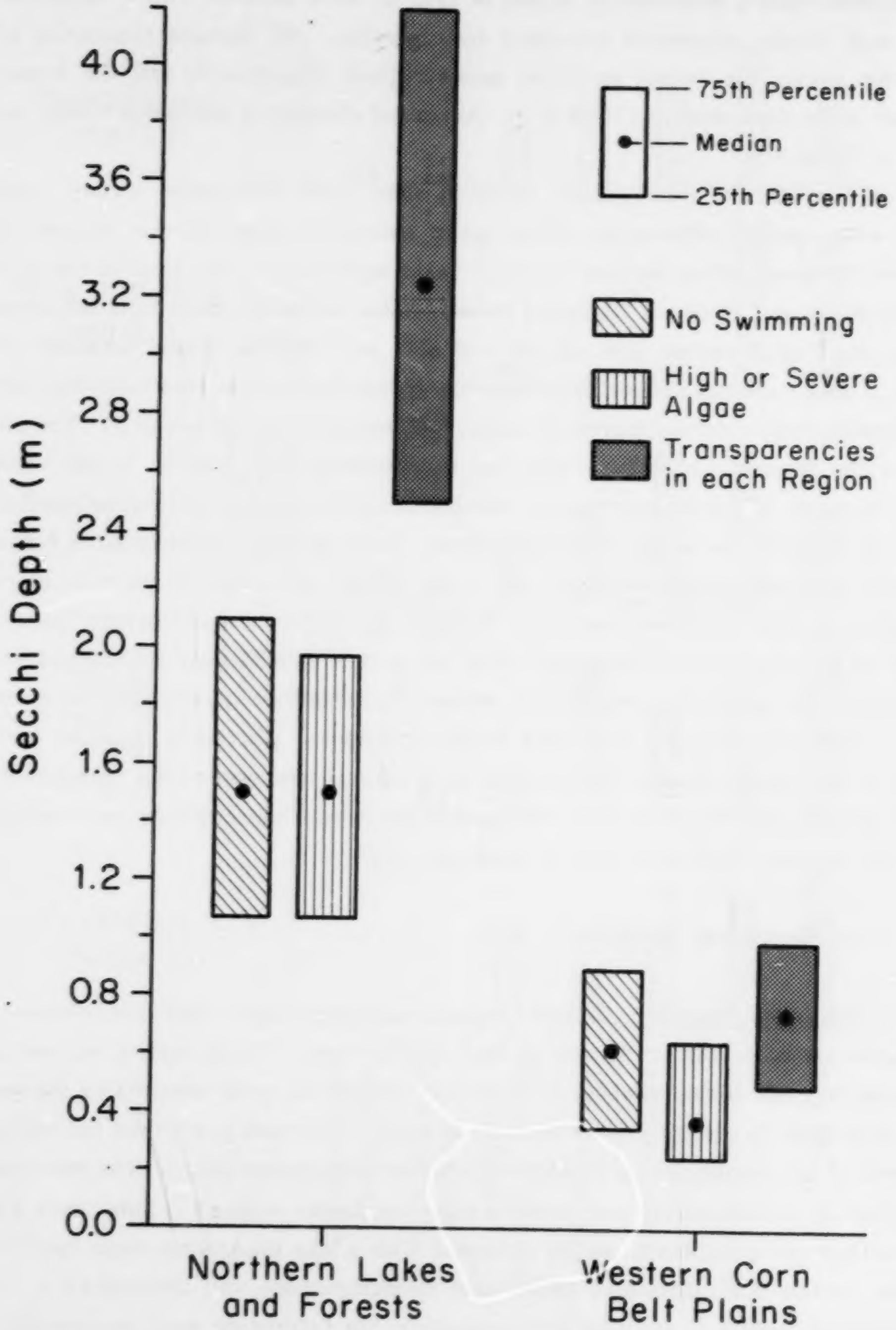

Figure 4-8. Correspondence between user perception and measured lake quality in Minnesota ecoregions (adapted from Heiskary 1989). Typical transparencies are for least impaired reference lakes representative of each region (interquartile range from Figure 4-6).

Published reports illustrate the results of both of these analyses with a variety of box plots, graphs, and tabular summaries organized by ecoregion. We include summaries to show the differences among the stream attributes across regions (Figure 4-9) and the important trends identified in the data analysis (Table 4-5). An initial estimate of attainable stream water quality appears in Table 4-6.

All of the stream water quality variables show some differences among ecoregions. In general, water quality differences reflect major land differences between regions to the north (Northern Minnesota Wetlands and Northern Lakes and Forests) and those to the south (Western Corn Belt Plains and Northern Glaciated Plains). Some variables reflect little influence of human activities (e.g., conductivity, temperature, and pH), but relate to natural landscape and climatic patterns. Other variables reflect a combination of human activities and landscape patterns (e.g., total suspended solids, nitrate/nitrite-nitrogen, total phosphorus and turbidity). The nitrate/nitrite values in the Western Corn Belt Plains are exceptionally high relative to the values in other regions, probably reflecting increases in nitrogen fertilizers used for row crop production in that region and extensive use of tile drainage systems. Some variables reflect mainly human activities (e.g., total ammonia, fecal coliforms, and 5-day BOD), and relate to patterns in point source discharges and cattle densities (including feedlots) that also follow ecoregional patterns.

Trends in important variables influenced by human activities are highlighted by a regional presentation. For example, a significant increase in nitrate/nitrite-nitrogen has occurred in the Driftless Area and Northern Glaciated Plains Ecoregions, whereas a decrease has apparently occurred in the North Central Hardwood Forests (though not statistically detectable). For total suspended solids, significant increases are seen in the North Central Hardwood Forests, Red River Valley and Western Corn Belt Plains Ecoregions (Table 4-5).

4.3.3.4 Lake Phosphorus Modeling--

The Minnesota Pollution Control Agency also uses three lake phosphorus models for quantitative estimates and prediction of lake trophic state. These require increasingly detailed data, from regional to site specific, as inputs for the models, with presumably the more detailed models providing increasingly more accurate outputs. The models are used for various levels of assessment of lake quality and projected response to management action. The most general model uses regionally defined coefficients derived from the studies outlined in Subsection 4.3.3. It links water outflow and phosphorus supply equations with a lake phosphorus mass balance model and empirical models that relate lake phosphorus to transparency and chlorophyll *a*. The values, summarized in Table 4-7, are used in two equations for calculating *water outflow* and *phosphorus supply* to a lake. An empirical mass balance model is used to calculate in-lake phosphorus levels that would result from these water and phosphorus loadings. The equations are:

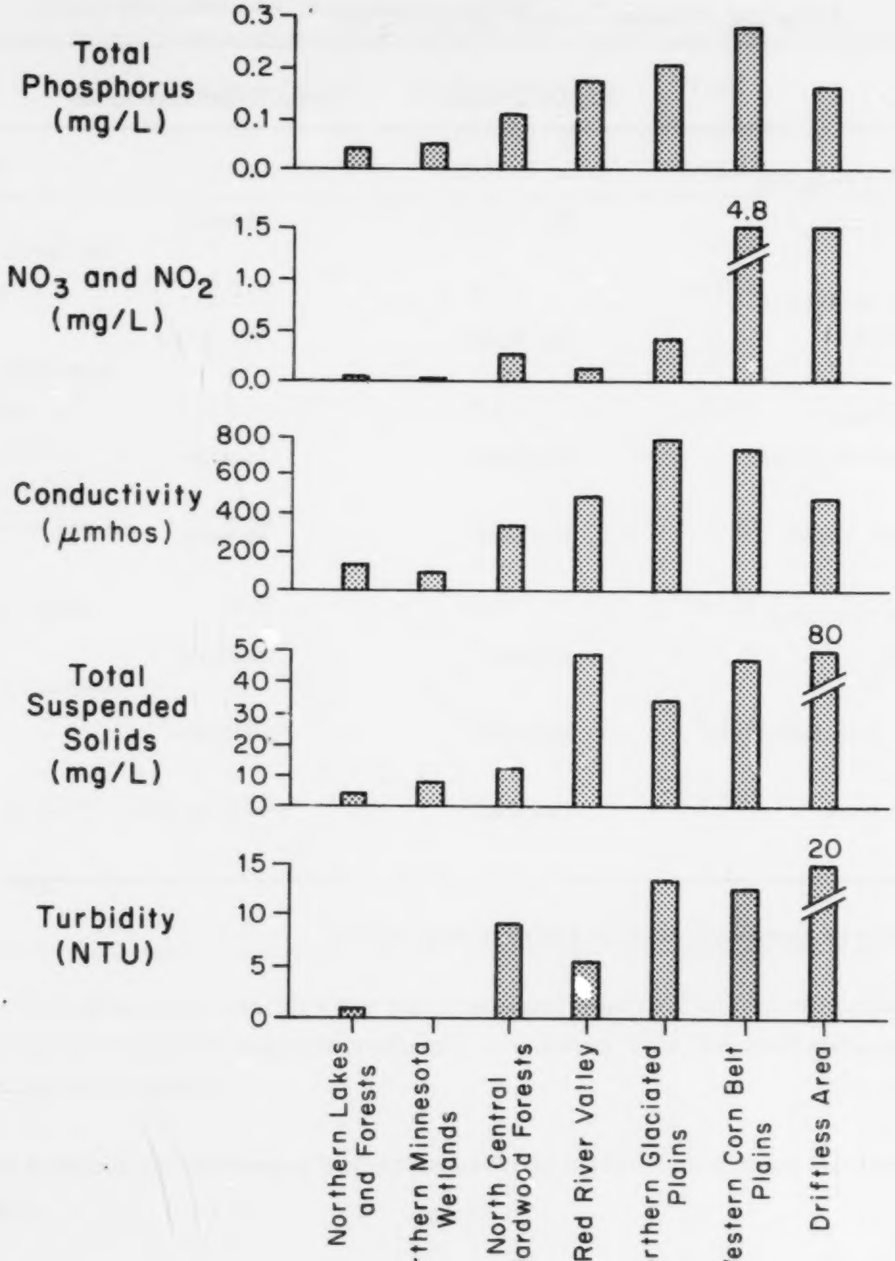

Figure 4-9. Comparison of selected regional water quality attributes in Minnesota streams (Minnesota Pollution Control Agency 1988a).

Table 4-5. Trends in Stream Water Quality for the Period 1973-1985 in Minnesota Ecoregions (Minnesota Pollution Control Agency 1988a)

Ecoregion	Nitrate + Nitrite	Total Suspended Solids	Ammonia
Northern Lakes and Forests	No Trend	Increase	Decrease
Northern Minnesota Wetlands	No Trend	No Trend	Decrease
North Central Hardwood Forests	Decrease	Increase[1]	No Trend
Red River Valley	Increase	Increase[1]	No Trend
Northern Glaciated Plains	Increase[1]	Increase	No Trend
Western Corn Belt Plains	Increase	Increase[1]	Decrease
Driftless Area	Increase[1]	No Trend	Decrease

[1] Statistically significant changes greater than $p = 0.05$.

Table 4-6. Preliminary Estimate of Attainable Stream Water Quality in Minnesota Ecoregions (Minnesota Pollution Control Agency 1988a)

Ecoregion	Nitrate + Nitrite (mg/L)	Total Suspended Solids (mg/L)	Total Phosphorus (mg/L)	5-day BOD (mg/L)
Northern Lakes and Forests	0.09	6.4	0.052	1.7
Northern Minnesota Wetlands	0.08	17.2	0.092	2.2
North Central Hardwood Forests	0.29	16.1	0.170	3.4
Red River Valley	0.20	56.5	0.322	4.2
Northern Glaciated Plains	0.52	65.5	0.271	4.5
Western Corn Belt Plains	5.62	57.5	0.340	5.6
Driftless Area[1]				

Streams used in Minnesota's ambient water quality program from 1973 to 1985 were culled to select those that were less impacted. Suggested attainable water quality is the 75th percentile concentration values for this set of streams.

[1] No data available, use estimates of best attainable water for the North Central Hardwood Forests Ecoregion.

Table 4-7. Ecoregion Variables Used in the Minnesota Lake Phosphorus Model MINLEAP (Wilson and Walker 1989)

Ecoregion	Runoff (cm/yr)	Precip. (cm/yr)	Evap. (cm/yr)	Atmos. Phosphorus Deposition ($kg/km^2/yr$)	Ecoregional[1] Stream TP ppb ($\mu g/L$)
Northern Lakes and Forests	23	74	61	15	52
North Central Hardwood Forests	13	75	71	30	148
Northern Glaciated Plains	5	64	76	20	1500
Western Corn Belt Plains	13	80	74	20	570

[1] Ecoregional stream TP is a calibrated value estimated from ecoregion lake data by adjusting stream phosphorus concentrations to give less biased predictions of lake phosphorus concentrations within each ecoregion. Note the differences between these values and observed stream values (Table 4-6 and Figure 4-9), particularly for the Northern Glaciated Plains. The routine monitoring program is believed to significantly underestimate average inflowing TP concentrations because high flow conditions (when stream phosphorus concentrations often increase substantially) are not adequately monitored.

Water Outflow = [Runoff x Watershed Area] + [Lake Area x (Precipitation - Evaporation)]

Phosphorus Supply = [Lake Area x Atmospheric Deposition] + [Watershed Area x Runoff x Ecoregional Stream TP]

This model is intended as a screening tool for estimating lake condition, using a minimum amount of data to identify problem lakes. It can be used to assess whether a particular lake is in better or worse shape than expected for the region (e.g., to identify lakes having unusually high or low measured phosphorus concentrations), given its location, morphometry, and hydrology. The results from this general assessment can be used to corroborate the results of the more detailed models, and may be useful for prioritizing lakes at a local level relative to the need for protection (if the study lake is of substantially higher quality than expected for the region) or restoration (if the lake is of substantially lower quality than expected).

4.3.3.5 Management Implications--

Important regional differences in both terrestrial and aquatic characteristics throughout Minnesota dictate that management of these resources take such regional differences into account. This is being accomplished in a variety of ways: regional summaries of terrestrial and aquatic characteristics, recognition of different achievable goals in different regions, recognition of different land use patterns that are partially responsible for degraded water quality, and exploration of various approaches for establishing quantitative goals, criteria, and methods to account for situations not readily fitting regional patterns. In various reports, Minnesota has characterized these regional differences and incorporated them into state management strategies, including the state's nonpoint source program, the Clean Water Partnership, that was developed with the flexibility needed to recognize regional differences. Table 4-8 summarizes management goals for lakes and streams of two regions that represent the kinds of issues addressed by Minnesota; Table 4-9 shows proposed numeric phosphorus criteria for lakes in the four lake ecoregions.

4.4 POTENTIAL APPLICATIONS AND FUTURE DIRECTIONS

Although this report and our research have focused on applications of regional assessment to surface water issues and management, the regional analysis approach described can be used to evaluate the extent and complexity of other concerns as well. A number of themes that are currently of interest are discussed in this section. Because the combination of terrestrial and climatic information used to develop the ecoregion map (Omernik 1987a) is pertinent to several of the issues, the map may be useful as an upper-level framework. However, as explained in Subsection 1.5.2, the relevancy of any framework to an intended use must be evaluated.

Table 4-8. Overview and Summary of Regional Characteristics and Management Goals in Two Contrasting Minnesota Ecoregions (summarized primarily from Heiskary and Wilson [1988], with information from a number of other sources)

NORTHERN LAKES AND FORESTS ECOREGION

Regional Characteristics:

Extensive stands of second growth forest.

Numerous lakes.

Moderate slopes, with steep slopes along the Lake Superior shore.

Historic and present land use associated with aesthetic, mineral, and timber resources.

Intensive land use (wastewater treatment facilities, logging) confined to small areas, not widespread.

Stream and Lake Water Quality:

Generally high quality.

Water quality in most streams and lakes comparable to that of minimally impacted sites.

Reference lakes typically have total phosphorus concentration of 14 to 27 μg/L (25th-75th percentile of values); average chlorophyll *a* less than 10 μg/L; maximum chlorophyll *a* less than 15 μg/L; Secchi disk transparencies from 2.5 to 4.2 m (25th-75th percentile of values).

Little seasonal variation in stream water quality.

Stream water quality problems are probably confined to isolated areas and involve nutrients or suspended sediment.

Management Goals:

Lake protection is a primary goal, especially for lakes supporting a coldwater fishery and lakes whose total phosphorus level is less than 15 to 20 μg/L.

Maintain the high transparencies and low chlorophyll *a* levels of these lakes.

Total phosphorus concentrations of 14 to 27 μg/L are reasonable and feasible for a majority of lakes in this region.

For coldwater fishery lakes, a goal for total phosphorus of less than 10 to 15 μg/L is desirable and feasible.

(Continued)

Table 4-8. Overview and Summary of Regional Characteristics and Management Goals in Two Contrasting Minnesota Ecoregions (summarized primarily from Heiskary and Wilson [1988], with information from a number of other sources) (Continued)

For lakes not supporting a coldwater fishery, a total phosphorus goal of less than 30 μg/L appears feasible; at or below this level, a goal of no measurable increase in trophic state is desirable.

At these levels of total phosphorus, algal scums would be rare and nuisance conditions (chlorophyll *a* concentrations greater than 20 to 30 μg/L) would occur less than 10% of the time.

Secchi disk transparencies of greater than 3 to 5 m would be expected more than 50% of the time.

For lakes with water quality lower than these goals, small reductions in total phosphorus should result in detectable aesthetic improvement (e.g., through increased lake clarity and reduced frequency of nuisance algal blooms).

A summary of suggested criteria is given in Table 4-9.

WESTERN CORN BELT PLAINS

Regional Characteristics:

Silt textured productive soils.

Gently rolling terrain; low slopes in most areas.

Dotted with shallow lakes.

Well developed stream drainages.

Agricultural practices well developed; row crop agriculture dominant.

Numerous small towns.

Extensive modification to natural drainage patterns.

Widespread agricultural impacts.

Stream and Lake Water Quality:

Average concentrations of water quality attributes are high and appear to have increased in streams since 1965 to 1970.

Nitrate/nitrite nitrogen concentrations are exceptionally high relative to other regions.

Lakes are shallow, with mean depth generally less than 3 m; most are polymictic; the few dimictic lakes tend to have lower total phosphorus concentrations than the others.

(Continued)

Table 4-8. Overview and Summary of Regional Characteristics and Management Goals in Two Contrasting Minnesota Ecoregions (summarized primarily from Heiskary and Wilson [1988], with information from a number of other sources) (Continued)

Lakes range from mildly eutrophic to hypereutrophic; bluegreen algal blooms or extensive weed growths are common.

Reference lake total phosphorus values typically are from 65 to 150 μg/L; average chlorophyll *a* ranges from 30 to 80 μg/L and maxima are from 60 to 140 μg/L; Secchi disk transparencies range from 0.5 to 1 m (25th-75th percentile of lakes).

Predominant uses of lakes are fishing and wildlife habitat.

Winterkill in lakes was common before installation of winter aeration devices.

Relatively few citizen complaints in 1986 (people probably know what to expect in this region).

Few permits issued for chemical algal control in 1986.

Management Goals:

Minimize extensive algal blooms.

Total phosphorus in the range of 50 to 70 μg/L is necessary to appreciably reduce the frequency of blue green algal blooms and allow Secchi disk transparencies in the 1 to 2 m range. This should be achievable in the deepest lakes in this region, but will be difficult in most others.

To improve recreational uses (swimming, aesthetics), transparencies should remain above 1 m; this would require an average total phosphorus concentration of 50 μg/L, a level achieved by less than 10% of the lakes in this region. A total phosphorus concentration range of 70 to 90 μg/L is a more feasible goal, but use for swimming would only be partially attained.

The few lakes that exhibit total phosphorus concentrations below 50 to 70 μg/L (e.g., the dimictic lakes) are unique for this region, highly valued, and should be managed with that in mind.

For other lakes, implementation of best management practices may be effective if internal phosphorus loading is a small fraction of lake total phosphorus loading. If internal loading is important, as it often is in this region, implementation of best management practices might not be sufficient to produce detectable changes.

Before expending lake restoration funds in this region, the expected responses of the lakes should be evaluated carefully because of the difficulty in producing detectable changes.

Table 4-9. Most Sensitive Lake Uses and Suggested Phosphorus Criteria for Minnesota Ecoregions (Heiskary and Wilson 1988)

Ecoregion	Most Sensitive Uses	Phosphorus Criteria
Northern Lakes and Forests	• Drinking water supply	< 15 μg/L
	• Cold water fishery	< 15 μg/L
	• Primary contact recreation and aesthetics	< 30 μg/L
North Central Hardwood Forests	• Drinking water supply	< 30 μg/L
	• Primary contact recreation and aesthetics	< 40 μg/L
Western Corn Belt Plains	• Drinking water supply	< 40 μg/L
	• Primary contact recreation and aesthetics	
	(full support)	< 40 μg/L
	(partial support)	< 90 μg/L
Northern Glaciated Plains	• Recreation and aesthetics (partial support)	< 90 μg/L

The basic principles of our regional analytical approach are common throughout each of the issues below. Namely, spatial environmental data is examined to delineate and characterize potential regions; inferences are drawn as to the relative risk in specific regions, or representative site data is analyzed to indicate the condition of regional sites under a particular set of influences.

Cumulative Impacts Assessment on Water Bodies - The extent of the effects on surface water quality from waterway modification, waste disposal, and terrestrial devegetation is essentially unknown. A regional framework can be used to organize and analyze environmental data to assess the cumulative effects of these management practices. Because Omernik's (1987a) ecoregions were delineated by considering the effects of a number of interrelated climatic and terrestrial environmental characteristics on regional patterns in water quality, the map should prove a particularly useful framework for this purpose.

Three types of assessment could be considered: attainable quality, current status, and best management practices. To assess attainable quality, data from relatively unimpacted sites within ecoregions and subregions, which would be delineated to sort within-region variability, would be compared with values from sites impacted to varying degrees by various perturbations. Regional water chemistry and species abundance and composition data from the sites could then be used to develop a quantitative community impact model. Current status would be determined by randomly selecting a separate, representative set of sites to be sampled at regular intervals. Values from these sites would be compared to the predicted attainable values and extrapolated regionally to assess cumulative impacts and temporal trends. Where available, historical data should also be examined from an ecoregional perspective to provide a greater temporal assessment. The effects on water quality from different management practices could be assessed by comparing data from relatively unimpacted reference sites with sites receiving *best management practices* or treatments of point source pollution.

Nonpoint Source Pollution - The issue of diffuse source pollution is closely related to the study of cumulative impacts on surface water quality. Effects on surface water quality from modification of water courses, irrigation return flow (e.g., increased soil and water salinity), terrestrial devegetation from farming, livestock grazing, and development, stockyard manure disposal, and chemical agents can be sorted through regional analysis of representative surface waters. A regional framework can be used to organize and analyze environmental data to assess the isolated and combined effects of various management practices.

Again, Omernik's (1987a) ecoregion map should be useful for such an evaluation. As with assessment of cumulative impacts on surface water, nonpoint source assessments could also be centered around analysis of attainable quality, current status, and best management practices. Attainable water quality would be estimated using data from regionally representative, relatively unimpacted sites. The attainable quality would represent a measure of reasonably achievable water quality, given the environmental characteristics and economic emphases of each region or subregion. Current status would be determined by randomly selecting a set of sites for data comparison with the least impacted sites. The effects on water quality from different management practices could be measured by selecting regionally representative sites that are subject to varying degrees of impact from single and combined practices. Effectiveness could be measured as differences between the achievable water quality and that produced in the presence of the best management practice.

Soil Erosion - Our agricultural soils are threatened by long-term loss of fertility from erosion due to management practices related to farming, timber harvest, livestock grazing, and urban and rural development. Environmental conditions affecting soil erosion, such as soil type, slope gradient, and aspect, potential areas of mass soil movement, drainage patterns, and climate can be mapped to delineate soil erosion regions. Within these regions, different management practices (e.g., irrigation patterns and intensity, tilling practices, timber harvest methods, livestock concentration and rotation patterns, vegetative cover conditions, and construction techniques) and associated rates of soil erosion can be compared. These comparisons can be used to determine which practices result in the least amount of erosion for each region. Thus, timber harvest locations, levels, and methods can be evaluated relative to regional conditions, as can timing and intensity of grazing allotments, and construction activity.

Endangered Species - Risks to threatened, endangered, keystone, and game species from pesticides can be evaluated by examining maps of known and potential habitats of the species of concern in concert with maps of pesticide application patterns. Potential habitats can be determined through analysis of coincident distributions of particular environmental characteristics (wetlands, vegetation, terrain features, etc.). Patterns of pesticide application can be estimated from county records of crops produced and the types and timing of pesticides applied to each crop. Potential pesticide dispersion can be estimated by geographic assessment of drainage patterns and soil characteristics. Acute direct effects and chronic indirect (foodchain, growth, disease, abundance) effects on species of concern can be assessed by field studies of areas expected to differ in impact. Potential areas for introduction or restoration of game or endangered species can be evaluated for suspected pesticide stress.

Biological Diversity - Local and regional patterns in environmental variables affect biodiversity and the impact of human actions on diversity. Habitat types or regions that are particularly rich in species, have great abundances of individuals, or support unusual communities with high rates of endemism can be mapped. Regional analysis of biogeographic and habitat data can be compared with species distributional patterns and abundance so that, where habitat conditions are desirable, managers can seek to increase those conditions on a regional scale; where conditions are undesirable, managers can attempt to reverse those trends, protect critical remnant ecosystems in the region, or expand or reconfigure refugia before species become threatened or endangered.

Environmental characteristics common among habitats or regions can be used to develop resource management policies that are more protective of biodiversity.

Groundwater Assessment and Protection - Groundwater aquifers may become contaminated by nonpoint sources of pesticides and fertilizers, naturally occurring chemicals, and point source toxics. Natural features, anthropogenic contributions, and human consumption can be spatially assessed to predict the relative risk of contamination of groundwater with respect to drinking water and wellhead protection. Some natural environmental characteristics that might be used for regional groundwater analyses include: bedrock porosity and faulting, soil permeability, presence of soil pans or lenses, known geological deposits of salts, cations, and metals, and frequency of surface water-ground water connections (wetlands, influent streams, soil channels). The spatial assessment of these characteristics would result in a map of groundwater regions. Overlaying the regions would be an array of anthropogenic impacts that might be assessed from information such as the frequency and location of wastewater well injections, existing well water chemistry, locations of industries producing water soluble/transportable contaminants, and type and intensity of agricultural (including irrigation, silvicultural and rangeland) practices.

Another concern related to groundwater quality is hazardous waste siting and assessment. Here, regional characteristics can be assessed relative to the effects of siting in any particular region. Additionally, proximity of proposed and existing sites to human settlements, ranges and migratory pathways of species of interest, groundwater recharge areas, surface drainage patterns, and distribution of surface waters and wetlands can be superimposed over the proposed site areas.

Global Climate Change - The effects of global climate change on crop production, human welfare, and biota may be predicted from regional geographic analyses. An analysis of current soils, potential natural vegetation, land-surface form, and climate has led to the delineation of Omernik's (1987a) ecoregions. Current species ranges, human population centers, and patterns of crops, forage, and forests can be analyzed in comparison with ecoregions to document present distribution. With accelerated climatic change, certain environmental variables are likely to be more stable over the next few decades (e.g., geology and land-surface forms) than others (e.g., soil potentials, vegetative cover, agricultural potential, and thus biotic habitats).

Quantitative variable response models can be developed to predict potential changes in environmental resource conditions. Projected climates for various areas can be substituted for current climates in the models. The reduction or increase in the predicted range of a particular species under various scenarios offers a quantification of the possible changes. Similar models for habitat requirements and physiological limits of species are commonly used in fish and wildlife management. Additionally, projected climates and predicted species ranges can be mapped to study the shift of the less stable variables over the more constant environmental characteristics.

4.5 SECTION SUMMARY

In this section, we have demonstrated how several state agencies have incorporated an ecoregion framework into ongoing regulatory and assessment processes. This framework has been used to establish biologically oriented standards in two states: in Ohio, numeric biocriteria were developed from measurements of fish and macroinvertebrate assemblages in least impacted reference streams; in Arkansas, refined use designations were developed from fish assemblage data obtained at least impaired reference sites. Also, in Arkansas, regional criteria for dissolved oxygen, turbidity and temperature were established. In Minnesota, this framework has been used to synthesize information on land and surface water characteristics in order to help develop a nonpoint source pollution program and regional lake management goals. We have closed the section with a discussion of areas of potential application of this regional approach, including assessments of cumulative impacts, nonpoint source pollution, soil erosion, endangered species, biological diversity, groundwater quality, and the effects of global climate change on terrestrial and aquatic habitats.

SECTION 5

REPORT SUMMARY

1. The United States is not a uniform landscape from border to border. However, it is not so complex that is impossible to recognize different natural and cultural land regions. These regions are relatively homogeneous areas where within-region environmental variability is less than among-region variability. Thus, a regional framework is a logical way to organize management of environmental resources.

2. Regions may be based on many themes. These may be very specific, such as regions of summer total phosphorus in lakes, or they may be general, such as aquatic ecosystem regions. Regions can be delineated at any level of resolution, depending on objectives.

3. Numerous regional frameworks have already been developed. Because of their widespread availability, a number of these have been widely used for management and reporting of resource conditions, often with misleading results.

4. In evaluating the utility of available frameworks for surface water assessment, we learned that frameworks have repeatedly been used for purposes other than those for which they were developed. This discovery led us to develop a synoptic approach that not only helps appraise the utility of existing frameworks, but assists in developing new, more appropriate frameworks. The result of our initial effort for assessing surface water resources is a map entitled *Ecoregions of the Conterminous United States*. Since publishing the map, we have subdivided ecoregions for more specific state level assessments, and aggregated ecoregions for more general national level assessments.

5. Three states have incorporated our national ecoregional framework into their ongoing regulatory and assessment programs. Arkansas developed ecoregion-specific biological use designations and regional criteria for dissolved oxygen, turbidity, and temperature of surface waters. Ohio established regional numerical biocritera for surface waters. Minnesota used a regional framework to synthesize information on land and surface water characteristics to accommodate the development of regional lake management. Other states are in various stages of investigating the framework for management purposes.

6. The steps of our approach include: (1) defining appropriate questions, related variables, and locations of concern, (2) identifying the environmental characteristics that affect, or are affected by, the variables, and obtaining spatial reference information depicting the distributions of these characteristics, (3) defining and delineating areas (regions) of relative homogeneity by synoptically evaluating the spatial distributions of the suite of characteristics,

and (4) obtaining numerical data to quantitatively evaluate the correspondence between the data and the regional framework.

7. Successful regional delineation depends upon careful selection of spatial reference information, awareness of the accuracy and level of resolution represented by the information, and comprehension of the interactions among natural and imposed environmental characteristics.

8. Successful evaluation of environmental data depends upon the quality, quantity, and spatial distribution of data values, and the use of appropriate analytical techniques.

9. Regional delineation and assessment techniques can be applied in many areas of environmental research and management. Some potential areas include: cumulative impact assessment, nonpoint source pollution, soil erosion, endangered species habitat, biological diversity, groundwater assessment and protection, and the environmental effects of global climatic change. Because the national ecoregion framework was based on coincident distributions of many terrestrial and climatic environmental characteristics, the framework may be appropriate for use in several of these areas.

SECTION 6

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APPENDIX A

References Used to Define and Delineate Ecological Subregions of Colorado

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APPENDIX B

Study Designs Used by State Agencies in Arkansas and Ohio

This information provides background for several examples used in the text and should be consulted for descriptions of rationale, design, and results. A list of references is included for each state.

ARKANSAS - Arkansas Department of Pollution Control and Ecology

Goal: Evaluate the physical, chemical, and biological characteristics of least disturbed streams in watersheds of various sizes within each ecoregion in Arkansas. Apply data acquired as part of this study to develop realistic water quality standards and designated uses.

Ecoregion Delineation: Arkansas contains parts of six ecoregions as delineated on *Ecoregions of the South Central States* (Omernik and Gallant 1987c). The regions are:

Arkansas Valley
Boston Mountains
Mississippi Alluvial Plain (aka Delta)
Ouachita Mountains
Ozark Highlands
South Central Plains

Watershed Sizes: A range of watershed sizes representative of each region was selected to include all possible beneficial uses for the streams. Watershed sizes varied from approximately 45 to 1,350 km^2, allocated into three size classes, 50 to 130 km^2, 260 to 520 km^2, and 775 to 1,300 km^2, for sampling over the three-year period of the study.

Site Selection: Lists of least impacted, candidate streams were developed from evaluating the locations of known dischargers and consulting the Arkansas Department of Pollution Control and Ecology staff to exclude streams with known pollution sources, including nonpoint source pollution problems. The lists were reduced by extensive field evaluation to confirm suitability as least disturbed, yet regionally representative, sites.

Sampling Periods: Two sampling intervals were selected to represent critical periods for aquatic life in Arkansas streams: (1) Late summer (August and early September) characterized by low flow, high water temperatures, and low dissolved oxygen, and (2) Spring spawning season (March) when dissolved oxygen requirements for fish reproduction are critical.

Streams were sampled from spring 1983 through fall 1985; a few streams were also sampled during spring 1986. Each stream was surveyed twice, once during spring and once during late summer; a survey required one week. Small streams were sampled the first year, intermediate streams the second, and large streams the third year.

Stream Attributes Sampled:

Chemical:	Dissolved oxygen (72-hour continuous measurements at two sites during the survey interval)
	Ammonia-nitrogen
	Orthophosphate
	Biochemical oxygen demand
	Total phosphorus
	Nitrate + nitrite nitrogen
	Chloride
	Sulfate
	Total iron
	Alkalinity
	Hardness
	Manganese
Physical:	Temperature (72-hr continuous at oxygen sites)
	Turbidity
	Total suspended solids
	Total dissolved solids
	Specific conductivity
Biological:	Fecal coliform
	Chlorophyll *a*
	Macroinvertebrate assemblages
	Fish assemblages
Physical Habitat:	Stream flow
	Stream gradient
	Mean channel width
	Mean stream width
	Mean stream velocity
	Estimated mean depth
	Stream substrate
	In-stream cover

Pool/riffle ratio
Riparian area
Bank stability
Percent canopy

Number of Stream Sites and Watershed Sizes by Ecoregion:

REGION	NUMBER OF SITES	WATERSHED SIZE (km^2)
Arkansas Valley	6	44 - 795
Boston Mountains	6	120 - 965
Mississippi Alluvial Plain	4	60 - 120
Ouachita Mountains	6	50 - 935
Ozark Highlands	6	45 - 1,360
South Central Plains	9	60 - 1,170

Estimated Costs (J. Giese, pers. comm.):

Total Cost[1]	$360K
Source	205(j) (CWA)
Duration	4 Yrs.[2]
Staff (FTE)[3]	6

Summary Reports: For greater detail, consult: Bennett et al. (1987), Giese et al. (1987), and Rohm, et al. (1987).

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[1] Includes 10-15% for equipment and supplies.

[2] Includes 3 sampling years and 1 year of data analysis and writing.

[3] Includes project leader, senior fish and macroinvertebrate biologists (full-time), data base manager, chemists, field technicians (part-time).

OHIO - Ohio Environmental Protection Agency

Data obtained as part of this study were supplemented with data on other reference streams from Ohio's routine monitoring program.

Goal: Evaluate attainable quality in streams throughout Ohio; obtain information on streams not impacted by point source or substantial nonpoint source pollution.

Ecoregion Delineation: Ohio contains parts of five ecoregions as delineated on Ecoregions of the Upper Midwest (Omernik and Gallant 1988). The regions are:

Eastern Corn Belt Plains
Erie/Ontario Lake Plain
Huron/Erie Lake Plain
Interior Plateau
Western Allegheny Plateau

Watershed Sizes: Watersheds were selected to be contained either completely within core or transitional parts of each ecoregion; a few were selected that crossed ecoregional boundaries. Watershed sizes ranged from 25 to 775 km^2. These were supplemented by reference sites from the Ohio Environmental Protection Agency's ongoing monitoring program, especially for large rivers. Supplemental data expanded the watershed size range to 2.5-17,000 km^2.

Site Selection: First, all watersheds that fell entirely within the cores or the transitional parts of each ecoregion were outlined on a 1:500,000-scale topographic map. These candidate sites were pared down to select those watersheds least impacted by human activity. Materials used to assess relative impact included:

Maps of human population density and census data.
Maps of land use, past and present strip mining, and streams impaired by strip mining.
Lists of important point sources occurring in the candidate watersheds.
Aerial photography of candidate watersheds.
Field examination of watersheds and potential sites to maximize physical habitat quality, to insure that obvious pollution sources were not overlooked.
Field experience and judgment of Ohio EPA staff.

Sampling Period: Streams were sampled over an 18-month period beginning in July 1983 and ending in November 1984. Approximately half the streams were sampled for biota and physical habitat characteristics during the first summer, and half during the following summer, with several sites sampled both summers. Water chemistry in all streams was sampled monthly over the entire period. Supplemental data collection followed the same protocol; data were obtained from 1979-1987.

Stream Attributes Sampled:

Chemical:	Alkalinity
	Hardness
	pH
	Dissolved oxygen
	Nitrate-, nitrite-, ammonia-, and Kjeldahl-nitrogen
	Total phosphorus
	Total organic carbon
	Magnesium
	Calcium
	Cadmium
	Chromium
	Nickel
	Zinc
	Iron
	Copper
	Lead
Physical:	Temperature
	Conductivity
	Total residue
Biological:	Macroinvertebrate assemblages
	Fish assemblages
Physical Habitat:	Substrate quality
	Instream cover
	Channel morphology
	Riparian zone and bank erosion
	Pool/glide and riffle/run quality

Number of Streams:

	Site type	Eastern Corn Belt Plains	Erie/Ontario Lake Plain	Huron/Erie Lake Plain	Interior Plateau	Western Allegheny Plateau	Statewide
Fish	Wading	7	10	21	34	41	113
	Boat	7	7	10	12	39	75
	Headwater	2	10	23	16	19	70
	Total	16	27	54	62	99	258
Macroinvertebrates		31	19	45	48	89	232

Estimated Costs (C. Yoder, pers. comm.):

Total Cost[4]	$480K
Source	205(j) (CWA)
Duration	4 Yrs.[5]
Staff (FTE)[6]	8

Summary Reports: For greater detail, consult: Larsen et al. (1986, 1988), Ohio Environmental Protection Agency (1987a, 1987b, 1987c); Whittier et al. (1987).

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[4] Includes 10-15% for equipment and supplies.

[5] Includes 2 sampling years and 2 years data analysis and writing.

[6] Includes project leader, senior fish and macroinvertebrate biologists (full-time), data base manager, chemists, field technicians (part-time).

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PLATE 1

ECOLOGICAL SUBREGIONS OF COLORADO

By ALISA L. GALLANT and JAMES M. OMERNIK

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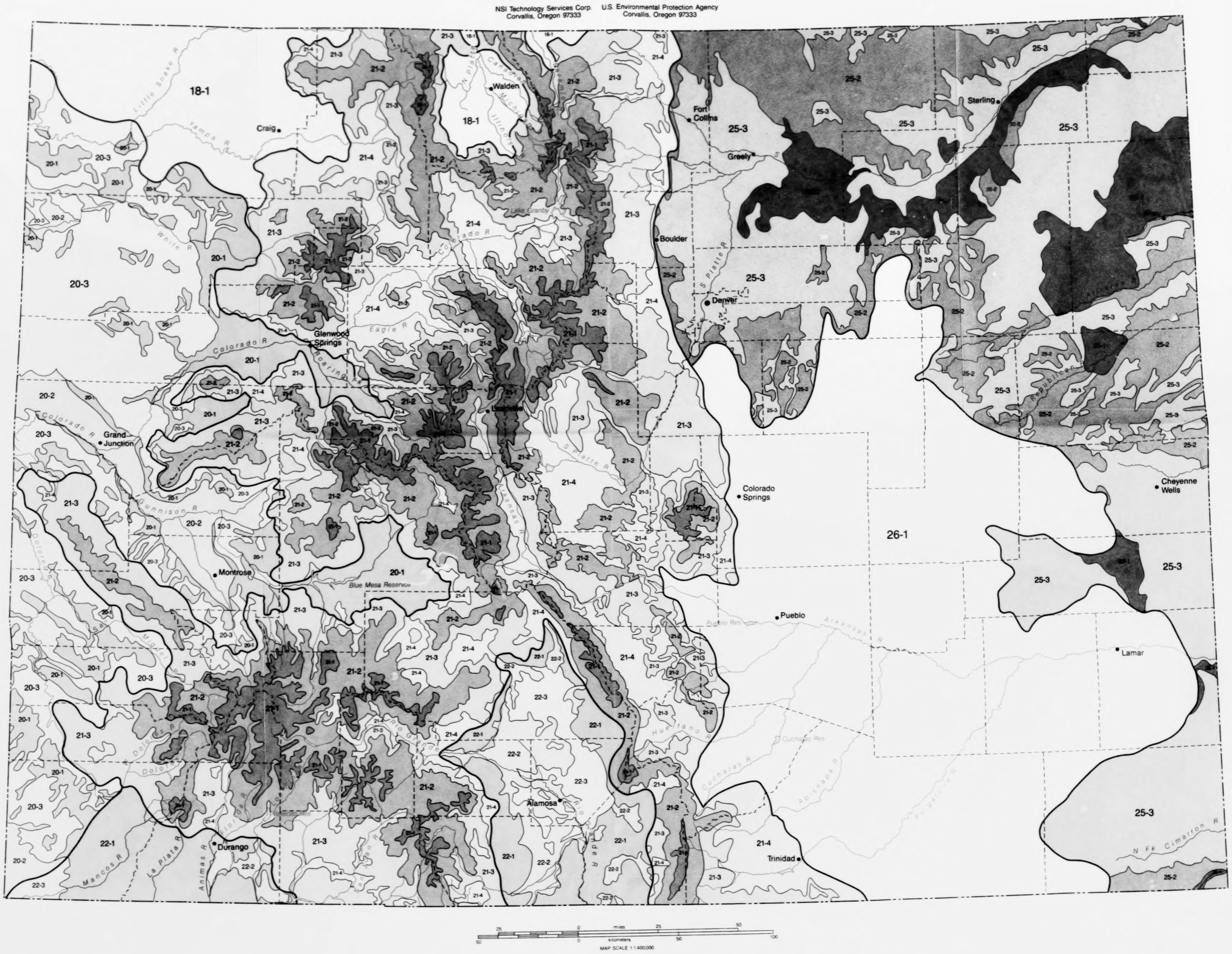

WYOMING BASIN (18)

18-1 Semiarid to Arid Shrublands

CLIMATE—Semiarid to arid. Much of subregion receives less than 300mm annually, but, in entirety, the area receives less than 400mm (drier in Wyoming, precipitation averaging 175mm in some areas). Precipitation mainly in spring and fall.

PHYSIOGRAPHY—Irregular basin terrain with isolated mountains and plateaus. Local relief generally greater than 30m, often greater than 120m (steep side slopes of uplands can have 180m of local relief).

LAND USE—Extremely low density rangeland for beef cattle and sheep.

VEGETATION—Widely scattered shrubs. Sagebush-dominated shrublands incluce big sagebrush mixed with various shortstem grasses (e.g., wheatgrass, needle-and-thread, Indian ricegrass). Saltbush-dominated shrublands include saltbushes, greasewood, various shortstem grasses. Rocky Mountain juniper and piñon pine on some uplands.

SOILS—Entisols.

COLORADO PLATEAUS (20)

20-1 Desert Shrublands

CLIMATE—Semiarid to arid. 200 to 400mm precipitation over most of subregion, a few areas up to 500mm.

PHYSIOGRAPHY—Irregular plains to tablelands with local relief commonly between 200 to 300m.

LAND USE—Rangeland. Of three Colorado Plateau subregions, this generally best for grazing, but quality still low.

VEGETATION—Sagebrush shrubland; includes big sagebrush, rabbitbrush, assorted drought-resistant grasses (e.g., wheatgrass, Indian ricegrass, bluegrass).

SOILS—Aridisols and Entisols.

20-2 Saltdeserts

CLIMATE—Arid. Less than 250mm precipitation annually, mostly in fall and spring.

PHYSIOGRAPHY—Nearly level to irregular valley floors.

LAND USE—Mostly rangeland for beef cattle and sheep. Irrigated agriculture concentrated in river valleys where there is perennial stream flow from neighboring mountainous ecoregions. Orchard crops (apples, peaches, pears, cherries), hay, grain, and vegetables (e.g., onions, beans) cultivated in these valleys.

VEGETATION—Saltbush shrubland; includes saltbush, greasewood, rabbitbrush, horsebrush, grasses (Indian ricegrass, galleta).

SOILS—Aridisols and Entisols.

20-3 Wooded Uplands

CLIMATE—Semiarid to arid. 200 to 400mm precipitation over most of subregion, greater than 600mm around Douglas Pass in Garfield County, CO.

PHYSIOGRAPHY—Tablelands; local relief often from 200 to 300m.

LAND USE—Rangeland for beef cattle and sheep. Of three Colorado Plateaus subregions, this generally worst for grazing (rockiest terrain, farthest from surface water supply, lowest concentration suitable forage).

VEGETATION—Juniper and piñon pine woodland. Grass and shrub understory includes wheatgrass, Indian ricegrass, grama, sagebrush.

SOILS—Aridisols and Entisols.

SOUTHERN ROCKIES (21)

21-1 High Elevation Tundra

CLIMATE—Cold, humid to arid. Annual precipitation from 750–1500mm, mostly as snow, but much is removed by strong winds.

PHYSIOGRAPHY—Mountaintops. Local relief 300–600m.

LAND USE—Wildlife habitat, recreation. Use limited by inaccessibility most of year (snow-free only 4–6 weeks, some portions perennially covered).

VEGETATION—Above treeline (starting around 3,300–3,600m elevation) vegetation such as low growth shrubs, cushion plants, and forbs. Forest-tundra interface sparsely colonized by stunted, deformed Englemann spruce, subalpine fir, limber pine, and bristlecone pine.

SOILS—Pergelic Cryumbrepts and Cryochrepts, formed largely from crystalline rocks, rock outcrops.

21-2 Cool and Moist Forests of the Middle to High Elevations

CLIMATE—Cool humid. 750–1,000mm annual precipitation for most of subregion, mainly as snow, remaining on ground well into summer months.

PHYSIOGRAPHY—Steep, forested slopes of Rocky Mountains from about 2,700–3,300m elevation. Local relief steep, often 300 to 600 or more meters.

LAND USE—Wildlife habitat, recreation, and mineral extraction. Grazing limited by climatic conditions, lack of forage vegetation, and inaccessibility from excessively steep terrain and lingering snowpack.

VEGETATION—Dense forests dominated by Englemann spruce and subalpine fir; some areas locally dominated by aspen. Sparse forest understory.

SOILS—Rock outcrops, Cryoboralfs and Haploborolls weathered from a variety of crystalline and sedimentary materials.

21-3 Warm and Dry Forests of the Middle to Low Elevations

CLIMATE—Warm, dry. Around 400–750mm annual precipitation, as snow and rain. Snow-free period at least four months.

PHYSIOGRAPHY—Lower to mid-elevation (1,700–2,700m) mountain slopes. Steep local relief, 300–400m.

LAND USE—Livestock grazing, wildlife habitat, mineral extraction, recreation.

VEGETATION—Variety of communities: aspen, Douglas-fir, ponderosa pine, Gambel oak, and piñon pine–juniper woodlands.

SOILS—Borolls, Boralfs. Derived from variety of crystalline and sedimentary rocks under variety of conditions existing between cold, humid, high elevation forests and warm, semiarid, low elevation shrubs and grasslands.

21-4 Low to Middle Elevation Semi-Desert Shrublands

CLIMATE—Semiarid. 300–400mm annual precipitation.

PHYSIOGRAPHY—Rolling to irregular terrain of lower to mid-elevation mountains. Local relief 60–300m.

LAND USE—Grazing. Areas adjacent to large perennial streams irrigated.

VEGETATION—Shrubland of greasewood, four-winged saltbush, shadscale, and sagebrush, often interspersed with grasses.

SOILS—Borolls. Derived from variety of sedimentary and crystalline rocks.

ARIZONA / NEW MEXICO PLATEAU (22)

22-1 Shrublands

CLIMATE—Semiarid, 230–450mm annual precipitation.

PHYSIOGRAPHY—Irregular plains, moderate to high relief plateaus, and open, low mountains. Local relief from 30m on irregular plains, to 300m or more near high tablelands.

LAND USE—Low density livestock grazing. Mostly beef cattle and sheep.

VEGETATION—Communities range from shrublands of big sagebrush, rabbitbrush, and winterfat to grasslands of western wheatgrass, green needlegrass, blue grama, and needle-and-thread.

SOILS—Mostly Argids, also Psammaquents and Orthents.

22-2 Irrigated Flatlands

CLIMATE—Arid. 200mm or less annual precipitation.

PHYSIOGRAPHY—Flat to low relief plains. Local relief minimal to a few meters.

LAND USE—Irrigated agriculture. Main crops include: barley, malt, alfalfa, small grains, hay, Irish potatoes, and a few other assorted vegetables.

VEGETATION—Originally shrublands dominated by shadscale saltbush and greasewood. Natural vegetation removed for cropland acreage.

SOILS—Mostly Argids, also Psammaquents and Orthents.

22-3 Saltdeserts

CLIMATE—Arid.

PHYSIOGRAPHY—Irregular plains of low to moderate relief. Local relief from several meters, to tens of meters, to 60m.

LAND USE—Low to very low density livestock grazing. Mostly beef cattle and sheep.

VEGETATION—Shrublands dominated by shadscale saltbush and greasewood; sagebrush, horsebrush, spiny hopsage, rabbitbrush, saltgrass and alkali sacaton also occur.

SOILS—Mostly Argids, also Psammaquents and Orthents.

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WESTERN HIGH PLAINS (25)

25-1 Rolling Sand Plains

CLIMATE—Semiarid. 200–300mm annual precipitation.

PHYSIOGRAPHY—Sandy hills. Local relief often around 15m.

LAND USE—Rangeland. Small plots of irrigated agriculture scattered throughout subregion where reliable groundwater supplies occur.

VEGETATION—Sand reed, bluestem, sand dropseed and sand sage.

SOILS—Ustic Torripsamments formed from eolian deposits.

25-2 Moderate Relief Rangeland

CLIMATE—Semiarid. 200–300mm annual precipitation.

PHYSIOGRAPHY—Irregular plains. Local relief usually from 15 to 30m, sometimes 45m.

LAND USE—Rangeland.

VEGETATION—Mainly blue grama, often with western wheatgrass, galleta, alkali sacaton and four-wing saltbush interspersed.

SOILS—Ustolls. Some Aridisols. Formed from sediments.

25-3 Flat to Rolling Cropland

CLIMATE—Semiarid. 200–300mm annual precipitation.

PHYSIOGRAPHY—Rolling plains. Local relief a few to 15m.

LAND USE—Dryland agriculture.

VEGETATION—Mainly blue grama, often with western wheatgrass, galleta, alkali sacaton and four-wing saltbush interspersed.

SOILS—Ustolls.

SOUTHWESTERN TABLELANDS (26)

26-1 Grasslands

CLIMATE—Semiarid. Much of area in Colorado receives 300–400mm precipitation. Large area in west central portion receives less than 300mm.

PHYSIOGRAPHY—Irregular plains and tablelands of moderate local relief, generally between 15–30m.

LAND USE—Rangeland. Exception occurs along Arkansas River where perennial water supply and sufficiently flat terrain coincide.

VEGETATION—Mainly blue grama, often with western wheatgrass, galleta, alkali sacaton, four-wing saltbush, sand dropseed, three-awn, sand reed, bluestem, sideoats grama, and yucca interspersed.

SOILS—Ustollic Haplargids and Camborthids, Ustic Torriorthents.

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PLATE 2
CONDUCTIVITY

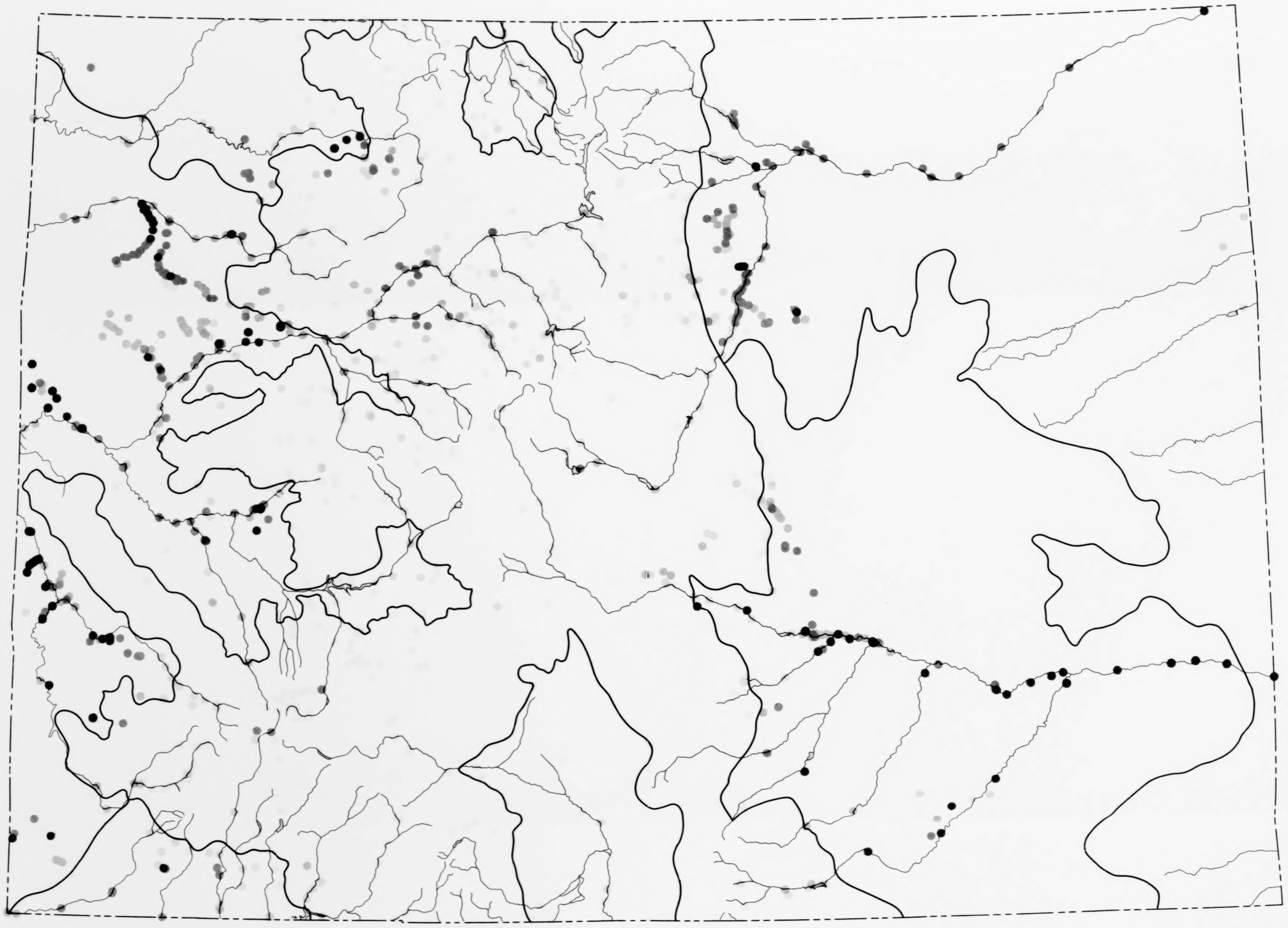

PLATE 2

CONDUCTIVITY

from

STORET Ambient Stream Stations in Colorado

by

Thomas R. Whittier

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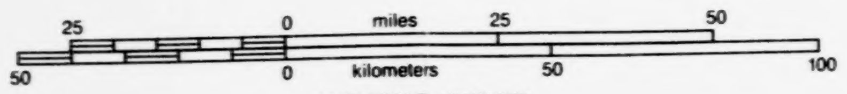

MAP SCALE 1:2,000,000

Station Medians (μmhos) for samples since 1/78

● <250
● 250–500
● 500–1000
● 1000–2000
● 2000–3000
● >3000

See Plate 1 for ecoregion names

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PLATE 3
KJELDAHL-NITROGEN

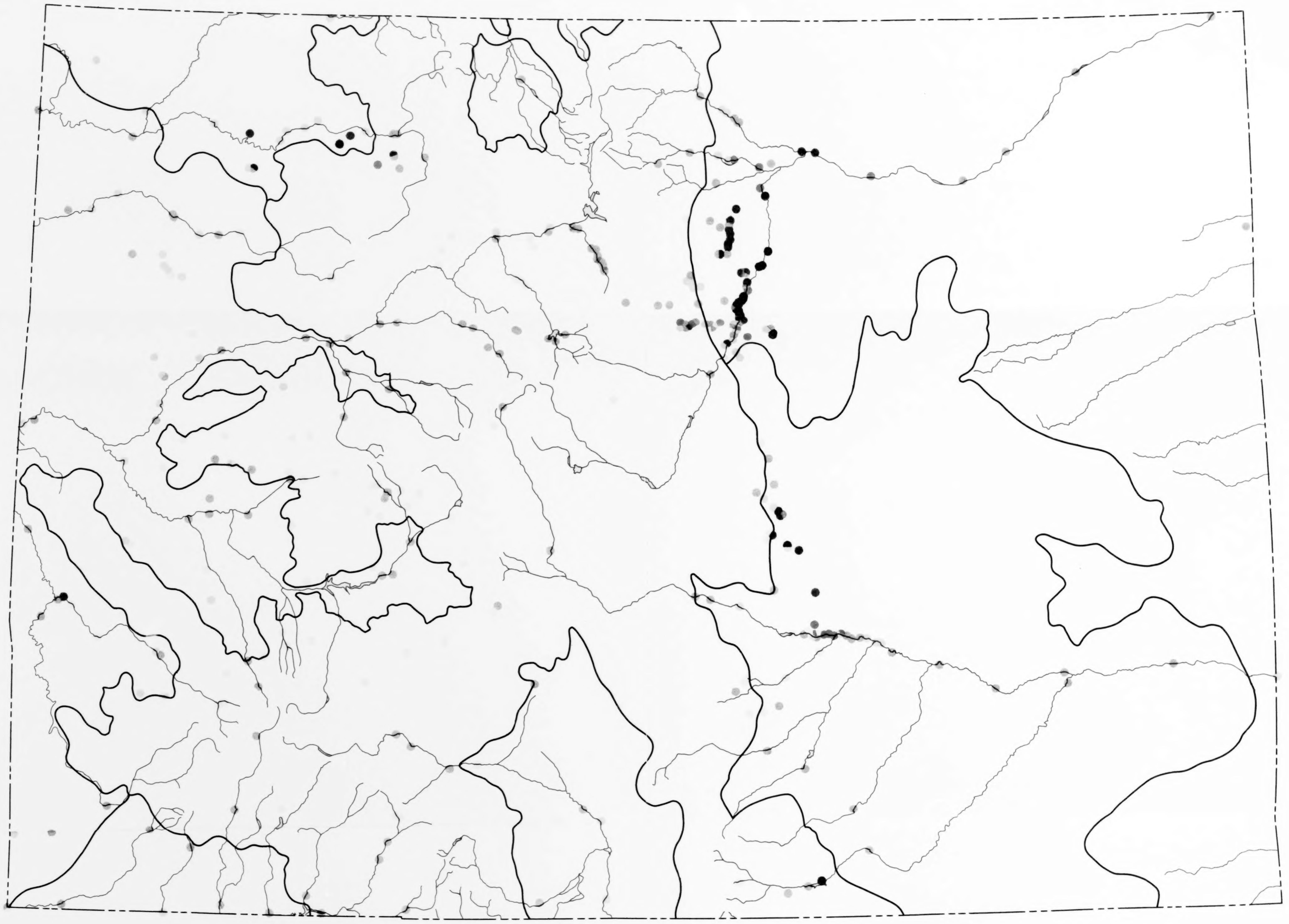

PLATE 3

KJELDAHL-NITROGEN

from

STORET Ambient Stream Stations in Colorado

by

Thomas R. Whittier

NSI Technology Services Corp.
Corvallis, Oregon 97333

MAP SCALE 1:2,000,000

Station Medians (mg/l) for samples since 1/78

●	<0.5
●	0.5–1.0
●	1.0–1.5
●	1.5–2.0
●	2.0–4.0
●	>4.0

See Plate 1 for ecoregion names

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